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TESTING PSYCHOMOTOR PERFORMANCE DURING SUSTAINED ACCELERATION

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NOTICES

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Recommendations, developed for the USAF School of Aerospace Medicine (SAM), concern a human psychomotor performance task which could be used to monitor, on a moment-to-moment basis, an operator's ability to perform satisfactorily during sustained acceleration stress. First, a survey was made of the literature on performance testing during G-stress, and/or on the relationship between physiologic and behavioral changes during acceleration. Next, an experimental program was planned and carried out, in which candidate tasks were evaluated under

20. ABSTRACT (Continued)

conditions of hypoxia and alcohol intoxication. Final recommendations were then made for: (a) a running memory task to measure a decrement in cognitive skills; and (b) an automated testing system, for installation on the SAM centrifuge, suitable not only for the recommended test but also for many other diversified tasks.

PREFACE

Gratefully acknowledged is the assistance of: Roy W. Thompson, of Technology Incorporated, who developed the system specifications described in this report; David Stolarski, of Technology Incorporated, who ably assisted in all phases of the experimental program; and Dr. Phelps P. Crump, Chief of the Design and Analysis Branch, Biometrics Division, of the USAF School of Aerospace Medicine, who provided valuable advice concerning statistical analysis of the data.

This publication is a slightly condensed version of the original contractor report.

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TESTING PSYCHOMOTOR PERFORMANCE DURING SUSTAINED ACCELERATION

INTRODUCTION

The purpose of this research program has been to develop a psychomotor task for monitoring human performance during sustained high-level acceleration. This task was also to serve as a real-time monitoring device, so that a performance impairment would be immediately apparent to the experimenter during the centrifuge run. In addition, the effort was to provide a record of performance changes occurring from moment to moment, thus permitting investigators to determine the degree of correlation between the physiologic and the behavioral state of the subject throughout the run.

Initially, a literature survey was made to ascertain the current status of performance monitoring during sustained acceleration and to abstract information on earlier attempts to determine the correlation between physiologic changes and performance decrements under G-stress. The results, already introduced in quarterly progress reports (21, 23), are discussed fully in the next section of this report. This information provides the reader not only with the necessary background on the behavioral effects of sustained G-levels, but also with facts which served as a basis for this experimental program, as sponsored by the USAF School of Aerospace Medicine (SAM). Further, this report presents details of an experimental program which lead to the recommendation for a performance task that fulfilled the contract requirements. Some of these later data were included in an earlier progress report (22). Finally, our recommendation is presented: (1) for a performance task to measure cognitive decrement in human subjects experiencing sustained acceleration; and (2) for an automated performance testing system to implement this task.

Throughout this report, standard acceleration nomenclature is used: e.g., $+G_z$ refers to acceleration through the longitudinal axis of the body, with the inertial resultant in a downward direction ("eyeballs down"); $+G_x$ pertains to forward acceleration, with a resultant tissue displacement towards the back ("eyeballs in"); and $-G_x$ acceleration produces anterior tissue displacement ("eyeballs out"). The $\pm G_x$ mode is also commonly referred to as "transverse" acceleration, while $+G_z$ is often termed "positive" acceleration. Magnitudes are expressed in multiples of the acceleration due to gravity.

EDITOR'S NOTE: The principal abbreviations and symbols in this report are listed and briefly defined on p. 60.

LITERATURE SURVEY

Categories of G-stressed Human Performance

Research on human performance under severe gravitational stress has been so extensive during the past two decades that only a selective survey of the resulting literature is feasible here. Hence, this section is devoted to a review of types of tests which--according to our selective literature survey--reliably measure performance decrement under acceleration. Especial consideration is given to those characteristics which make these tests suitable or unsuitable for inclusion in the research program.

Experimental results are divided into three performance categories: visual, complex motor, and cognitive. These classifications are somewhat arbitrary, as some of the material reviewed could reasonably have been placed in more than one.

The "Visual Performance" section deals with that sensory system which is the primary information channel in most aerospace operations. Hence no attempt has been made here to include other sense modalities; for vision not only has received by far the greatest attention in centrifuge research over the years, but also permitted the greatest experimental flexibility because of the various stimuli that can be employed.

The "Complex Motor Performance" section concerns those tasks which have relatively large motor involvement, and which also incorporate sensory and cognitive functioning. The tasks discussed pertain to trading and piloting performance, and to simple and discriminative reaction-time skills. (Not included are investigations of grosser body movements, e.g., the degree of head or limb movement possible under various G-loads; for such performance measurements are too insensitive for our present study. Information on topics of this type, and on other topics outside the scope of this report, is available in refs. 13, 32, 35, 51. (The results of some work concerning auditory input are described under "Complex Motor Performance" in the subsection on "Reaction-Time Tasks.")

The "Cognitive Performance" section deals with tasks which assess the higher mental processes (e.g., memory, mathematical skills, and complex pattern discrimination).

Finally, a "Review and Conclusions" section presents an approach to test selection and describes some general features that should be incorporated, if possible, into the test ultimately chosen.

Visual Performance--Vision remains man's most important source of information about his environment, and is crucial in aerospace operations. The study of the effects of acceleration stress upon sensory input has been limited primarily to vision and visual perception. Visual degradation remains one of the first, and most dramatic, subjective consequences of accelerative stress. Because of the importance of the visual sense and its susceptibility, much of the research to date on human performance under acceleration has involved the study of vision. The dimming or the loss of peripheral and central vision are, in fact, the accepted endpoints for many human acceleration experiments.

This report section deals with five problem areas which may be listed in approximate order of visual processes complexity:

(a) Light-detection thresholds
(b) Contrast thresholds
(c) Visual acuity
(d) Ocular motility and pupil dilation
(e) Critical fusion frequency

(a) Light-detection Thresholds

Zarriello et al. (65) studied light-detection thresholds using four peripherally located green test lights, and one centrally located red light. Two of the peripheral test lights were located at 80°, and the other two at 23°, to the right and left of the subject's visual axis. The purpose was to determine whether the location of the test lights farther from the subject's central visual axis might be more sensitive for indicating early visual decrement than the standard 23° test light. The luminance of the test lights was approximately 5 millilamberts (mL) during a series of centrifuge runs between $+3G_z$ and $+7G_z$. In this study, 115 subjects were used and, in nearly all cases, the 80° peripheral lights were lost before the 23° lights. The time between 80° light loss and blackout (defined as central light loss) was approximately 0.4 sec longer than the time between the 23° light loss and blackout. The mean difference in G force between the near and far peripheral light loss was approximately 0.3 G_z, and it was concluded from their data (65) that 80° light loss provides an earlier warning of the imminent loss of central vision. The authors (65) point out, however, that the slight increase in time to blackout offered by the use of the 80° peripheral test lights may be of limited usefulness in actual G-stressed conditions. White (61) investigated changes in the visual thresholds of human subjects by using a modified Hecht adaptometer. The modified adaptometer incorporated features that allowed for the automatic presentation of light flashes, and for control of flash intensities by the subject. Since centrifuge runs must normally be limited in duration, a modified form of the psychophysical method of limits was employed. Between 8 and 14 upper and lower limit threshold determinations were made during each centrifuge run. The author omitted threshold determinations made while the centrifuge was accelerating to peak G, and therefore

his data represent information at specific acceleration levels. In this study (61), two 3° diam test light patches were used: one, foveal; the other, centered 7° temporally on the retina. The test flash occurred once per second with a flash duration of 200 msec. Only one experienced subject was used in this experiment. Each centrifuge run lasted 1.25 min, and was followed by a 2-min rest period. The data show that foveal thresholds, as compared with values measured at +1 G_z approximately doubled at +3 G_z and tripled at +4 G_z. Peripheral thresholds at +3 G_z and +4 G_z are three and four times, respectively, their equivalent +1 G_z values. In addition, repeated exposures to acceleration produced a small but significant decrease in visual sensitivity.

Brown and Burke (5) used a similar technique to study +G_z tolerance and reaction-time to luminances of peripherally located test lights. In this case, test lights were located either 28° 22' or 7° 24' from the subject's visual axis. The subject was allowed to "dark adapt" for 5 to 10 min before the run began. The two luminance levels of the test lights were: 4560 mL and 0.025 mL. The subject responded by pressing a switch when he perceived the test light. A red fixation light was provided for the subject to view during a run. Results from this experiment show that acceleration tolerance (measured as the G-level at which subjects did not respond to a light within 1.5 sec of onset) was higher for the brighter and more central test lights. Furthermore, reaction times increased significantly as the acceleration level increased: but the amount of this increase was not dependent upon the luminance of the test flash. The authors (5) state that reaction-time variability across subjects is so high that this measure probably does not offer a realistic and reliable endpoint for accelerative stress.

Decreases in visual light sensitivity have been observed under transverse (±G_x) accelerations as well, but at higher G levels than are necessary to produce a decline in sensitivity for the +G_z mode. For example, Chambers (11) reported some decline in peripheral sensitivity at +6 G_x, and a marked narrowing of the visual field by +12 G_x, with frequent central vision loss (blackout) at +15 G_x. Smedal et al. (57) reported results similar for both plus and minus transverse acceleration.

(b) Contrast Thresholds

The ability of subjects to detect visual stimuli at low levels of contrast has also been investigated as a function of accelerative stress. Braunstein and White (2) studied contrast acuity degradation in human subjects, exposed for 90 sec, to accelerations of 1, 2, 3, and 5 Gz and of 1, 2, 3, 5, and 7 +G_x. In this experiment (2), each subject responded to a light test patch, visible against a diffusely illuminated background, by operating a button to signal the appearance or disappearance

of the test patch. Background levels of 0.03, 0.29, 2.9 and 31.2 foot-lamberts (fL) were used. At all background luminance levels, contrast acuity decreased with increased $+G_x$ or $+G_z$ acceleration--although the effects of <u>positive</u> acceleration on contrast acuity were greater than those of <u>transverse</u> acceleration. (For example, the mean threshold contrast at +5 G_z with a background luminance of 5 fL was 2.5 times that obtained at the +1 G_z control level. The +5 G_x value at this background luminance level was only 1.3 times greater than the +1 G_x control.)

(c) Visual Acuity

Unlike simple light-detection decrements, which appear to be primarily the result of retinal or cerebral ischemia, visual acuity degradation under acceleration is apparently the result of mechanical distortion of the visual apparatus. The observed impairment of visual acuity seems best explained in terms of: crystalline lens displacement; a change in the eye's refractive power or focal length; change in corneal curvature; or lacrimation.

White and Jorve (62) studied near and far visual acuity (binocular and monocular) under $+G_z$ acceleration. They used four postural arrangements (seated, prone, supine, and semisupine) to modify the effects of decreased cerebral blood flow. This technique permitted assessment of any gross visual disturbances that were not primarily related to retinal or cerebral ischemia. A Bausch and Lomb OrthoRater was used to measure visual acuity under control and experimental conditions. The subject viewed a checkerboard slide and was asked to state the position of the test target. All subjects had considerable centrifuge experience and uncorrected visual acuity of 20/20 in both eyes. The range of acceleration values was 1 - 8 G, with a slow rate of onset in order to allow compensatory cardiovascular responses to occur. The AF-Navy G-4A G suit was worn only during the runs made with the subject seated.

The experimental results (62) show that loss of visual acuity was significantly and progressively related to increased gravitational stress, regardless of its direction. The authors state that decreased cerebral blood flow cannot be used to account for observed changes in visual acuity under accelerative stress. They postulate that gravitational stress effects on visual acuity may be attributed to: changes in the eyeball or refracting surface shapes; crystalline lens displacement; or effects on autonomic nervous system (such as anxiety or fear). Of these three theories, the authors (62) favor the lens-displacement hypothesis.

Smedal et al. (56) photographed a placido disk corneal reflection at -4, -6, and -8 G_x in order to study the degree to which corneal deformation occurred. This study was prompted by an earlier work [Smedal et al. (55)] in which transient visual acuity impairment was observed under negative transverse acceleration, and was postulated to be a function of corneal surface distortion. The photographs showed no distortion of the cornea itself, but intermittent lacrimation above

$-6\ G_x$ did distort the placido disk reflection. Smedal et al. (57) further investigated visual functioning under positive and negative transverse acceleration. The parameters included visual acuity, corneal deformations, and accommodative ability. No significant results were shown on the tests, except for a tendency to diplopia. The authors (57) suggest that subjective reports of blurring vision under $-G_x$ acceleration may be related to lacrimation, and that blurring under $+G_x$ acceleration may be related to grayout produced by retinal ischemia if the acceleration stress is prolonged.

Frankenhaeuser (30) studied $+3\ G_z$ acceleration effects on the visual acuity of three test subjects. The duration at peak G was from 2 - 10 min. The subjects indicated verbally the position of the gap in a test figure, and percent errors were calculated for each subject.

The results showed a significant increase in percentage of errors during $+G_z$ acceleration stress. Control performance scores ($+G_z$) before and after centrifugation were not significantly different from each other. The acuity degradation resulting from $+3\ G_z$ exposure was calculated to be 16%. This figure corresponds very closely with the data of White and Jorve (62), at $+3\ G_z$, in which they determined the loss to be 19%.

Similar research was performed by White and Riley (64), using the Wright Air Development Center (WADC) Human Centrifuge. They determined, under various levels of illumination, the impairment of instrument reading ability associated with $+G_z$ stress. Photographs of the dials in this experiment were shown 12 at a time to each subject, who read each dial to the nearest unit. Some were scaled in units from 0 to 100, while the others were graduated by fives without unit gradations. The panel of dials was located approximately 80 cm from the subject's eyes. The five luminance levels were 42, 4.2, 0.42, 0.042, and 0.004 mL. Acceleration levels ranged between $+1\ G_z$ and $+4\ G_z$. The subjects wore anti-G suits, so that peripheral dimming would not be expected below about $+5\ G_z$.

The results (64) indicated that, for panel luminances of 42, 4.2, and 0.42 mL, no significant increase in total errors could be determined from $+1\ G_z$ (control) to $+3\ G_z$. With panel luminances of 0.042 and 0.004 mL, however, total errors did increase from $+1\ G_z$ to $+3\ G_z$--and decreased as a function of brightness values studied. Reading-time scores for the illuminated dials varied in a way similar to the total error scores.

(d) Ocular Motility and Pupil Dilation

Beckman et al. (1) used a 16-mm motion-picture camera and a TV camera to record and view the ocular movements and pupillary reactions of human subjects undergoing $+G_z$. Two onset rates were employed: rapid, in

which peak G was attained in less than 10 sec; and slow, in which peak G was reached in approximately 14 - 28 sec. The two onset rates were chosen, as desired, for either of two purposes: to prevent cardiovascular compensatory reflexes from occurring (rapid onset); or to allow the full compensatory effects to occur (slow onset). Peak G duration times were from 15 - 60 sec, with peak G levels for individual subjects ranging from a low of $+3.5\ G_z$ to a high of $+7.0\ G_z$. Alternating peripheral test lights were presented to the subject, who was instructed to fixate each light, as carefully and for as long as possible. The length of illumination was varied from 0.5 to 1.5 sec in a random order.

Of the 60 subjects, all exhibited limitation of ocular movements under acceleration (LOMA), at points between the subjects' grayout and blackout points. Blink rates at these levels either decreased or ceased altogether. Pupil dilation began at approximately the time of peripheral vision loss and reached a maximum at the subjects' blackout acceleration level. Some of the experienced centrifuge subjects were partially able to overcome the tendency towards LOMA by exerting extra effort. The resulting movements, however, were ataxic. Some could open and close the eyelids, but extra effort was again required.

A modified skin-diver's mask was then placed over the respective subject's face, and a negative pressure of 30 mm Hg was generated by a vacuum pump. With the evacuated mask, vision was restored at blackout acceleration levels, and eye coordination movements were maintained. The pupils were less, but still partially, dilated. Ophthalmologic observation of the retinal vessels of the subject during blackout-level accelerations showed that, when the negative pressure mask was worn, the emptied retinal vessels were immediately filled.

A visual tracking task was also performed, using the experimenter's finger or a free-swinging pendulum as a target. The subject was asked to track the movement of the finger, or pendulum, while his cerebral circulation was reduced or arrested through occlusion by a cervical cuff. After 5 - 6 sec of cerebral anoxia, eye movements typically ceased, with the eyes coming to rest in the midline fixation. After the experiments, subjects indicated that they could see the moving finger of the experimenter, but were unable to track it with their eyes. Some subjects noted visual field narrowing, blurring, and blackout. In some cases, audition remained after complete visual impairment. (No statistics on the audition effects were presented, however.)

The authors (1) propose that dilation of the pupils may be a quantitative and reproducible indicator of each subject's grayout G-level, although no significant statistical relationship was shown between G-levels and pupil-dilation responses (when sampled across subjects). The authors (1) further suggest that the limited ocular motility may result from hypoxia of the cerebral hemispheres and, in addition, retinal hypoxia may exist.

(e) Critical Fusion Frequency

Critical fusion frequency (CFF) is that frequency at which discontinuous light flashes appear to become continuous or steady. Keighley et al. (39) measured the CFF of subjects exposed to G-levels from +2.5 G_z to +3.2 G_z for 45 sec, and the results showed no change in threshold. The mean CFF at peak G was only 0.18 Hz lower than the +1 G_z control. A second series of runs was undertaken, using negative pressures of -25 to -34 mm, to test the goggle apparatus. With the use of this apparatus G-levels of +3.4 G_z to 4.8 G_z were tolerated by the subject before visual loss or dimming was exhibited. Results of this series, as compared with those of the +1 G_z control runs, showed a statistically significant reduction in the CFF (-1.35 Hz S.D.).

In the third series, negative pressure was applied to only one eye of the respective subject. The peak-G level in this instance ranged from +2.8 G_z to 4.5 G_z. In all of these runs, the CFF was significantly lower (1.96 Hz S.D.) than in the +1 G_z controls. According to the authors, the decrease in CFF of these runs was attributable to decreased cerebral circulation rather than to retinal ischemia.

(a - e) Review and Conclusions

In order to design a psychomotor performance task which affords the necessary reliability and adaptability, it is necessary to determine limits within which man can perform that task. The ideal psychomotor performance task, for use in a high acceleration environment for sustained periods of time, should incorporate sensory inputs suitable for the reliable measurement of small performance decrements at levels above approximately +7 G_z or +14 G_x.

Visual inputs to such a psychomotor task should permit detection of gradual reductions in performance. Assuming a subject can see at all after, for example, 45 sec at +9 G_z, the visual stimuli should undoubtedly be of a high luminance, high contrast nature. If one assumes that peripheral dimming has occurred and that the subject is relying principally on central vision, the task should probably avoid any unnecessary eye movements; for by this time the subject's gaze would be limited to the midline position (1). Peripheral test lights would be of little or no value at such high-acceleration levels. Because a loss of acuity would be expected at the high sustained G-level, the design of any visual display (such as an instrument dial, or a tracking display pattern) might have to be as simple as possible.

In brief, to maintain adequate visual perception with a psychomotor performance test designed for prolonged high-level acceleration (above +7 G_z or +14 G_x), the following five stimulus requirements should be satisfied:

(1) High luminance levels of the selected display.
(2) High contrast ratios of images in the display.
(3) Exclusion of peripheral visual inputs.
(4) Use of simple detail display image(s).
(5) Positioning of the visual display on, or near, the subject's ocular midline position.

Complex Motor Performance

Tracking and Piloting Tasks

Studies concerned with the assessment of tracking and piloting proficiency during sustained acceleration stress have been popular at numerous centrifuge installations. Various acceleration environments have produced performance decrements in many of these experiments. The popularity of this type of study has been largely due to the realism that can be achieved through tracking tasks--and hence to the value of such tasks in predicting the performance of a pilot or astronaut in an operational situation. Commonly, a visual display is used to present certain "flight" information (perhaps aircraft orientation relative to the horizon) and to require the subject to control the craft in some fashion (such as maintaining straight and level flight, or pursuing a moving target). Centrifuge studies involving such tasks have been undertaken--not only to determine the range of acceleration environments over which man can perform effectively (including magnitudes, vectors, durations, and rates of onset), but also to investigate the manner in which G-stress interacts with certain variables (such as the type of control system, the aerodynamic characteristics of the simulated aircraft, the restraint system employed, the time lags built into the display, and the effects of practice). Because the volume and diversity of these studies precludes a comprehensive review at this time, our study provides a cross-section of the major experiments in this area, with emphasis upon those tests showing significant degradation under acceleration, and those illustrating important points in the use of tracking tasks to study G-stresses.

Fletcher et al. (29) utilized a compensatory tracking task that was found to exhibit a slight degradation at accelerations as low as $+2\ G_z$. In compensatory tracking as distinguished from pursuit tracking, the operator attempts to compensate for movements of a target by keeping it in a specified location on the display. A pursuit display, on the other hand, contains two moving elements: a target; and an indicator (such as a pointer) which the subject attempts to keep aligned with the target. In this study (29), the task involved bringing the subject's aircraft onto a pursuit course with a target aircraft moving both horizontally and vertically, and then maintaining the pursuit long enough to release a missile and guide it to the target. The subject controlled his aircraft with respect to pitch and roll. Three principal effects were noted:

First, a higher degree of control was achieved with a right-hand controller (which required only wrist movements and forearm rotation) than with a standard center joystick.

Second, cumulated vertical and horizontal error scores indicated that tracking began to worsen at only +2 G_z, although the difference, even at +4 G_z, was relatively small. Thus this test, while sensitive to G-stress, was not severely affected at the relatively low levels investigated. Had higher G-loads been employed, a sudden severe performance decrement might have resulted.

Third, considerable intersubject variability and practice effects were observed, indicating that extensive preacceleration training should be provided for tasks of this type.

A somewhat similar performance task, at the University of Southern California (USC) centrifuge installation, used sustained transverse (+G_x) acceleration by Kaehler (38). He utilized an oscilloscope display on which a horizontal line—representing the subject's own aircraft--could move either vertically (to indicate a pitch error) or by rotation about its center (to indicate roll error). The simulated aircraft motions were complex, representing flight under turbulent conditions. The subject's task was to maintain straight and level flight, using a right-hand controller in which the subject's wrist was the center of rotation for both pitch and roll modes. This carefully controlled study yielded two principal results:

First, the mean integrated error increased (for both pitch and roll) as the G-level increased from +1 G_x to +3 G_x, and from +3 G_x to +6 G_x. Error scores approximately doubled from the +1 G_x to the +6 G_x condition.

Second, the effects of exponential time lags built into the system were significant. (An exponential lag of 1 sec means that, if the control is moved a certain amount, the output on the display will require 1 sec to attain 63% of its ultimate displacement.) Tracking performance was considerably worse for a short time lag (0.1 sec) than for longer lags 1.0 or 2.0 sec). In addition, performance deterioration under acceleration was most pronounced for the 0.1 sec lag. The significance of this result is that the degree of time lag in a particular experiment may affect the magnitude of the acceleration-induced decrement, and perhaps also the G-level at which a decrement first occurs.

Summers and Burrows (58), also at USC, used a compensatory tracking task, which was similar to that of Kaehler (38). However, the display now contained a moving horizon and a fixed aircraft symbol; and the subject controlled the aircraft with a right-hand stick assembly, 12.7 cm long, which had a maximum travel of $\pm 30^{\circ}$ in each axis. This study (58) demonstrated a tracking decrement at +4 G_x and +6 G_x, but the decline was statistically significant only for the pitch mode. The authors suggest that this difference was due to a motor factor; for, with the control stick that was used, pitch-correction movements were in the same direction as the acceleration. Hence no differences were obtained between plus and minus transverse accelerations. Vehicle dynamics

("good" vs. "bad" handling characteristics) were found to affect tracking performance significantly, but no interaction was noted between vehicle dynamics and acceleration level. This finding conflicts with that in some studies (discussed subsequently), in which poor vehicle-handling characteristics resulted in decrements at lower G-level.

Many highly sophisticated studies investigating the role of acceleration stress upon piloting and tracking efficiency have been conducted at the Aviation Medical Acceleration Laboratory (AMAL), Johnsville, Pennsylvania. The centrifuge and the pilot's task have been described in detail in numerous sources [e.g., Chambers (11), Creer et al. (27)]. Basically, the pilot attempted to track a randomly driven target while piloting a simulated vehicle reentering the earth's atmosphere. The centrifuge was operated as a closed-loop system, so that certain linear acceleration components varied according to the pilot's input to the system. The target, appearing as a dot on the face of a cathode ray tube (CRT), was driven by the sum of a set of four sine waves, of varying amplitudes and frequencies. In addition, roll and pitch attitudes were displayed on the face of the CRT. Additional flight information appeared on the pilot's console. In flying the simulator, the pilot kept the aircraft reference indicator aligned with the constantly moving target. The control system found to be most efficient [Creer et al. (26)] was a finger-operated, two-dimensional, side-arm controller used in conjunction with toe pedals.

This tracking task (27) was chosen largely because of the degree of realism it afforded the pilot. In addition, because of the heavy workload imposed upon the pilot by the requirement to fly the vehicle as well as to perform the tracking task, the performance changes due to the G-stress would be more pronounced (27).

Creer et al. (26) investigated the influence of various acceleration vectors and magnitudes, as well as vehicle dynamics, upon tracking proficiency. The maximum acceleration magnitudes were +6 G_z, +6 G_x and -6 G_x, for 2.5 min. These investigators found that for a relatively easy control task, involving heavily damped vehicle oscillations, no tracking decrement occurred at any acceleration level. In the lightly damped case, however, which produced approximately 20% greater errors at 1 G, performance deteriorated markedly above 4 G and was relatively independent of the direction of the acceleration. These results indicate the importance of using a demanding task to show early performance decrements. This point was underscored by Sadoff and Dolkas (53), whose data showed a moderate decline above ±6 G_x for a well-damped vehicle, but a rapid decline above ±4 G_x for a lightly damped vehicle. Another significant point is that control performance is no less effective at $+G_z$ acceleration than at $\pm G_x$, provided no serious visual impairment occurs.

Chambers and Hitchcock (15) also emphasized the importance of the overall difficulty of the respective task--and the resulting effects on G-stressed performance. In general, the more inferior the aerodynamic characteristics of the simulated vehicle, the greater the likelihood of inferior human performance under G conditions.

Creer et al. (27), by using higher G-levels than those in the 1960 study, were able to differentiate clearly between the different vectors employed. All runs lasted 2.5 min, and vehicle motions were well-damped in this study. Between +6 and +9 G_z, performance dropped rapidly, while only a slight decrement was observed up to +14 G_x. This difference was attributed primarily to the serious visual degradation occurring above +7 G_z. The error score for the $-G_x$ vector was greater than that for $+G_x$, but did not exhibit the sudden dropoff characterized by the $+G_z$ data. Here also, visual problems (due, in this case, to excessive lacrimation), rather than cognitive or motor difficulties, were believed to have produced this difference.

An additional observation (27) was that tracking error was elevated during the onset of acceleration; after the centrifuge attained a steady velocity, the performance improved rapidly and then stabilized. This effect was attributed to pilot vertigo, produced by angular acceleration as the centrifuge was brought up to the desired speed. During this initial period, error scores were directly related to the rate of G onset, with a rapid decrement being produced by rates greater than 0.75 G/sec. This difference in tracking performance due to angular accelerations should be considered when a task of this type is used for monitoring. If performance is monitored in an experiment where acceleration is continuously increased until an error criterion is attained, spurious tracking error due to vertigo could result in incorrect conclusions about performance decrement produced by linear acceleration.

Brown (3) also discussed this problem. He noted that pilots, due to their experience in real airplanes often exhibit greater control difficulties resulting from anomalous angular acceleration than do non-pilots. Clearly, a performance task <u>not</u> susceptible to vertigo effects would therefore be desirable.

Sadoff (52), using the AMAL centrifuge, found the tracking decrement under sustained acceleration to be due largely to failure to respond adequately to higher frequency target oscillations. This information suggests that tasks with high-frequency input components may be more likely to show early effects of acceleration. Another observed effect is an increased difficulty, at higher G-levels, of dividing attention efficiently between various tasks, or between various components of a given task. For example, Chambers and Hitchcock (15) have described a study requiring control of flight-path angle, as well as pitch, roll, and yaw angles. Under +15 G_x acceleration, error scores increased dramatically but not uniformly across all features of the piloting task. Pitch control, which required almost continuous adjustment, was only slightly affected in the dynamic run; but the yaw mode, in which only occasional corrections were required, showed a fivefold increase in mean integrated error. Because the pilots were unable to concentrate on more than one or two aspects of the task, they apparently chose to concentrate on the most demanding components. Brown (3) has reported a similar

finding, in which performance of one control component ("vehicle coordination") was actually improved during acceleration, because the fluctuating acceleration attracted increased attention to this component, apparently at the expense of another component (vertical tracking) which required less attention. With this type of result, the main difficulty is ascertaining the respective extent to which the observed degradation is due: to the acceleration rate per se, and to a change in priorities. Accordingly, for monitoring purposes, a test should probably be designed which--although complex--nevertheless would involve a single dependent variable. If several separate yet interrelated task components must be employed, priorities should probably be established through some type of "payoff" structure, to decrease the likelihood that the subject will change his tradeoffs halfway through the task.

Chambers and Nelson (16) have reported another tracking task used successfully to show decrement resulting from positive and transverse acceleration. The pilot monitored a TV screen on which an inverted-T figure moved horizontally and vertically, and rotated through angles of up to 180^{o}. He attempted to damp the motions of this figure with a 3-axis fingertip controller, mounted in-line with his forearm rather than perpendicular to it. For a 2-min test run, $+G_x$ acceleration produced a gradual increase in error scores to $+10\ G_x$, and then a very large increase to $+14\ G_x$. Performance at $+5\ G_z$ and $-5\ G_x$ (the highest levels tested) showed considerable error increase. The authors (16) suggested that the rate of stick movement might be a useful monitoring variable because, in a given trial, differences appear earlier than do overall system errors. Moreover, total cessation of stick movement, due to unconsciousness of the subject, would be more immediately apparent than would differences in error scores.

A similar finding of a gradual performance decrease up to a certain acceleration level, beyond which performance declined rapidly, was made by Clarke et al. (17) in a study on the WADC centrifuge. Subjects attempted to keep two needles centered on a small target area by means of a sensitive two-dimensional side-arm controller that they manipulated with finger and wrist motions. A 170-sec acceleration profile was employed, with a peak at $+16.5\ G_x$; total time above $+8.5\ G_x$ was 50 sec. Average performance for two experienced subjects dropped from approximately 90% time-on-target at $+1\ G_x$ to about 20% at $+16.5\ G_x$. Most of this decrement, however, occurred between $+10\ G_x$ and $+16.5\ G_x$; at the highest levels visual loss was probably an important contributing factor. Significantly, these results--which are quite straightforward for experienced subjects--vary much more for subjects with little or no actual practice in the task at levels above 1 G (despite extensive training under static conditions). Although performance decrement may occur earlier for the inexperienced subjects, the greater variability makes these data more difficult to interpret. Consequently, experienced centrifuge riders appear to be a wise choice in most situations.

Tracking tasks unrelated to aircraft or space-vehicle simulation have also been used by some investigators to study the effects of acceleration. For example, Little et al. (44) obtained interesting results using a discontinuous 2-dimensional task, in which 2 lights on a cross of 10 horizontal and 10 vertical red lights were illuminated simultaneously. The subject was required not only to move a control-stick in order to match up (and illuminate) the corresponding horizontal and vertical green lights adjacent to the red lights, but also to hold the stick in the appropriate position for 0.2 sec. Performance was measured by the number of problems successfully solved within 15 sec. Subjects were tested at +5 G_x, +7 G_x, and +9 G_x, with 90 sec at peak acceleration. The results show a performance decrement which is more significant under dynamic conditions than under static conditions; but this test was not sufficiently sensitive to distinguish reliably between the three acceleration levels. One of the most interesting findings, however, was that of a strong "anticipation" effect. In a 60-sec preacceleration period, performance declined markedly between the first and the final 15-sec intervals. This effect, presumably caused by apprehension, is somewhat surprising, for only experienced centrifuge subjects participated in this study. A similar anticipation effect was evident for heart rate, and has also been observed by Brown (3).

In summary, Chambers (14) has discussed pilot performance under accelerative stress. He has provided the following useful list of 15 general characteristics of piloting impairment which were observed particularly under high transverse acceleration:

"1. <u>Increase in error amplitude as G duration and amplitude increases</u>. Error amplitude is used most frequently as an indicator of performance. The vast majority of research on human behavior under acceleration has been done on tracking error amplitude scores. These scores are concerned with the difference between the obtained response and the desired response. Assuming that the subject can perform the task satisfactorily during static tests, any large tracking errors obtained during acceleration may be attributed to the stress.

"2. <u>Lapses or increasing unevenness and irregularity of performing the task</u>. From time to time, the subject's performance may falter or may even stop temporarily. The subject is unable to maintain his performance at a consistently high level of proficiency. These may be called lapses, or expressions of increasing irregularity, and they usually increase in frequency and duration as the adversity of the acceleration stress is increased. Lapsing is characterized by a very

high level or almost perfect performance for a period of time and then the occurrence of relatively large errors. Following this brief lapse, performance again returns to normal, only to be followed by another lapse.

"3. <u>Performance oscillations</u>.

"4. <u>Falling off or reduction in proficiency on some parts of a task while maintaining proficiency on other parts</u>. Cessation of performance may occur on some parts of the task.

"5. <u>Changes in phasing and/or timing of task components</u>.

"6. <u>Reduction or cessation in performance output of some task components</u>.

"7. <u>Inadvertent control inputs</u>. These continue to be one of the most frequently encountered types of performance error during centrifuge simulations of spacecraft. These may be described as the insertion, by the astronaut, of specific control inputs which are not intentional and of which he is unaware.

"8. <u>Failure to detect and respond to changes in the stimulus field</u>. This occurs particularly often when the G force is from head-to-foot and blackout or grayout results. In such cases, the peripheral vision fails and responses to lights or other stimuli on the periphery also fail. This same failure to note changes in the visual field also becomes a leading factor when the array of dials and meters (containing both primary and secondary instruments) face the subject. Under acceleration attention tends to be focused on the primary instruments, and changes in secondary instruments may not be detected.

"9. <u>Errors in retrieving, integrating, storing and processing information</u>.

"10. <u>Changes in the rate of performance or the sudden initiation of performance components non-essential to the task</u>. In one particular example, subjects were required to press a button at least once per second while performing a tracking task under

acceleration reaching +10 G_X. One subject's rate of pressing tended to increase with acceleration until a final upper limit of nearly 250 responses per minute was reached. This contrasted sharply with the tendency of some subjects to hold the response button in the depressed position during peak exposure.

"11. Response lags and errors in timing. Increases in latency of response to discrimination stimuli. Also, there may be large changes in timing of component response sequences, or gross misjudgments of the passage of time.

"12. Overcontrolling or undercontrolling, as during a transition phase.

"13. Omission of portions of simple tasks, or of parts of complex perceptual motor tasks. These omissions occur especially during overload when the subject may not process all of the stimulus information, such as the inputs necessary to perform the secondary parts of the task at the originally achieved level of proficiency.

"14. Approximations. The pilot's behavior becomes less accurate, although the task does not increase in difficulty level. His responses become less precise, but minimally adequate to meet the required criterion of proficiency.

"15. Sterectyping of responses and movements regardless of the stimulus situation. All of the stimuli appear to have an apparent equivalence to the subject during prolonged stress, for example."

These 15 points by Chambers (14) demonstrate that complex psychomotor tasks, such as tracking and piloting, can be used successfully to ascertain performance decrement due to acceleration. Many of the control tasks hitherto utilized were designed to reflect the aerodynamic characteristic of specific vehicles. Hence, such tasks are probably too complicated to serve as "all purpose" tests under various experimental conditions.

In the use of piloting tasks to measure skilled performance under G-stress, the chief advantages are: realism and relevance to actual operational situations. On the other hand, the disadvantages should not be overlooked. One problem in using this method (instead of simply asking a pilot whether or not he can fly his vehicle "adequately" under certain

accelerative conditions) lies in defining what should be considered "error." Chambers (14) has pointed out that error is relatively easy to quantify in a pure tracking task. In a more realistic but less structured piloting task, however, there are many ways to achieve the same end result; and the particular maneuvers made by the pilot to reach this goal often cannot be labeled "correct" or "incorrect."

A second problem in using this method lies in determining the source of the impairment--that is, the specific sensory or cognitive ability affected by the acceleration. In some cases, the elusiveness of this information may not be a serious drawback; but, in less task-oriented experiments, such information can be highly desirable and ultimately of great value. Clearly, in the designing of a performance test, much thought must be given to its potential range of uses. In brief, will the advantages of a complex and highly realistic flight simulation warrant such factors as expense, subject training time, and experienced pilot time?

Reaction-Time Tasks

Among the unresolved issues remain the effects of acceleration on simple and discriminative (choice) reaction time (RT) to visual and auditory stimuli. Seemingly, RT is lengthened under accelerative stress; but the locus of this effect (sensory input, higher order processing, or speed of movement) has not yet been determined.

A few studies have failed to find significant RT decrements under moderate G-stress. Brown and Lechner (6) report an experiment by Kennedy et al. (40) showing no difference in simple RT to visual stimuli, up to the point of peripheral light loss. At higher G-levels, however, trials showing abnormally long RT's were discarded as being due to "inattention." Franks et al. (31) also failed to show an increase in simple RT to either visual or auditory stimuli for accelerations from +2 G_z to +8 G_z (except for visual stimuli immediately preceding blackout). In addition, Canfield et al. (8) found relatively slight effects in a discriminative RT task in which the subject moved a switch in 1 of 4 directions, in response to the directional relationship between a red and a green light appearing on a display panel. Subjects were tested in 15-sec sessions at either +1 G_z, +3 G_z or +5 G_z. No differences in mean RT were found, except for the first half of the trials, on the first 2 days of the 4-day experiment. These differences--apparently due to the novelty, or fear, associated with the testing situation--disappeared by the 3rd day.

The apparent learning (or practice) effect is a theme that appears in other studies of the results of acceleration. Frankenhaeuser (30) employed a fairly complex discriminative RT task in which the subject made 1 of 2 responses (pressing a switch located in either hand) to 1 of 5 combinations of 3 colored lights. Acceleration level was +3 G_z for a total of 5 min. The average RT under acceleration was longer than

during the pre- and postcentrifugation tests, but the effect was more pronounced during the first 2 min of the run than during the last 2 min. This result again shows that practice on a task apparently can overcome some of the effects of G-stress; long-term practice, however, would seem not to produce the same effect, as the author reports no clear differences between subjects with different amounts of previous centrifuge experience.

Chambers and Hitchcock (15) devised an RT task involving a 1:1 correspondence of 4 stimuli (lights in different positions) with 4 responses (activating switches with different fingers). In a given block of trials, the subject performed continuously for 25 responses--with each correct response, another light was illuminated. During 1 acceleration run at +6 G_X, 3 blocks of trials were given. Each subject received a total of 3 acceleration runs. The results, presented as the unweighted sum of normalized time-and-error scores, indicate that performance was: relatively poor during the first block of trials during acceleration; worse during the second block; but substantially improved in the third block. These results seem to show again that subjects can adapt considerably to the effects of acceleration and overcome initial performance decrements. Unfortunately, the authors (15) do not indicate whether similar effects were observed across the 3 acceleration runs. It would also be interesting to see their original data, in order to observe the differences between speed and accuracy decrements, and to determine the relative magnitudes of the effects of $+G_X$ acceleration, as compared with those in other studies.

A study by Brown and Burke (5) has already been discussed (under "Visual Performance," in "Light Detection Thresholds") in connection with the variables of target luminance and location, and is mentioned here in connection with the following point. Under $+G_Z$ acceleration, the speed decrement may possibly occur at lower G-levels for a dim target (0.025 mL) than for a bright one (4560 mL). This result should be substantiated; for it parallels the finding, from complex tracking experiments, that performance declines earlier for difficult tasks than for easier ones.

Two additional studies demonstrating significant effects of acceleration ($+G_Z$) on simple RT are those of: Burmeister [reported in Brown and Lechner (6)], who used a light signal and found RT reduction during 30-sec runs at +3 G_Z and +4 G_Z; and Canfield et al. (7), who used either a light or a buzzer and found decrements for 15-sec runs at +3 G_Z and +5 G_Z. The latter study (7) is particularly important for its comparison of visual and auditory sense modalities. Highly significant RT increases (for both +1 G_Z vs. +3 G_Z) (and +3 G_Z vs. +5 G_Z comparisons) were obtained for both the visual and the auditory signals. Since RT is known to vary inversely with stimulus intensity, these increases may be due to a peripheral rather than to a central effect: namely, a reduction in the sensitivity of the sense organ. Two facts, however, provide evidence against this interpretation. The first is

the authors' claim, based upon reports from the subjects, that no grayout or blackout of the visual system had occurred in this study. (If any grayout occurred, it was too slight to be noticed.) The second fact is that, although visual decrements are well-known consequences of acceleration, no studies yet show comparable reductions in auditory sensitivity under G-stress [Roth et al. (51)]. Therefore the highly similar results obtained for auditory and visual RT at relatively low acceleration levels would seem to implicate, not the sense organs, but some higher order processing of the input or response decision mechanisms.

This type of problem (determining the locus, or source, of a performance decrement) has been given scant consideration to date. It seems clear to the present reviewers that studies specifically designed to isolate various cognitive components, such as those pertinent to a choice RT situation, would contribute greatly to the understanding of human capabilities in an acceleration environment.

Cognitive Performance--When subjects are exposed to G-levels high enough to cause dimming and blackout, consideration must be given to the nature and extent of cognitive impairment likely to result from the altered blood flow to the cerebral hemispheres. If the G-level is high enough, complete loss of consciousness can occur--sometimes followed, upon awakening, by a period of disorientation, confusion, or amnesia (4). Such altered states of awareness have also been observed immediately preceding complete unconsciousness (18). Obviously it is important to understand the kind of cerebral impairment to be expected as the subject approaches the point at which he can no longer function adequately, and to determine the type of tasks likely to be most strongly affected by this impairment. Unfortunately, our knowledge in this area remains quite incomplete. Some studies have been directed toward this question, however, and are summarized in the remainder of this report section:

The discrimination of elements in relatively complex visual arrays is one aspect of cognitive performance that has been studied under G-stress. Comrey et al. (24) investigated their subject's ability to perceive minor differences in visual detail at low levels of positive acceleration, below which serious sensory impairment was expected to occur. The task required that the subject look at a series of photographs containing five similar items (such as boats, clocks, and shoes), one of which was in the center, with the other four surrounding it. Only one of the surrounding items was identical to the item in the center. The subject was required to identify this identical item, by location, as rapidly as possible. For each centrifuge run, 15 of these 5-element pictures were presented simultaneously on a large poster; the measure of performance was the number of correct identifications made within 15 sec. The subjects (who were not experienced centrifuge riders) wore anti-G suits and were tested at +1, +2.5, and +4 G_z, with 15 sec at peak G. The results indicated that some decrement occurred at +4 G_z, but only for the first half of the runs on each day of the experiment. These findings again illustrate the point that a time-dependent factor (perhaps a diminished susceptiblity to distraction, or an improved

physiologic compensatory response) can often overcome the decrements initially observed. Frankenhaeuser (30) also investigated this test of perceptual speed and found no decrement for sustained runs at +3 G_z.

Attempts to measure color discrimination and color-naming ability have yielded few significant results, at least at the low-acceleration levels tested. Frankenhaeuser (30) administered the Ischihara test for color deficiency at +3 G_z and found no changes from the 1 G_z level. She also studied color-naming speed via the Stroop test, which compares the differences in time taken: (a) to read a lengthy repetitive list of color names (red, green, yellow, blue); (b) to name these colors when presented as a string of differently colored circles; and (c) to name these colors when presented as a string of differently colored words, when the words themselves are the names of noncorresponding colors (for example, if the word "blue" was written in yellow ink, the subject was required to say "yellow"). A significant speed decrement at +3 G_z was found for tasks (a) and (b), but not for (c). Thus the ability to overcome the verbal interference produced in task (c) was not hindered at this acceleration level. Furthermore, the decrement in color discrimination and naming was similar to that obtained in the simple reading of color names, suggesting that acceleration may have affected verbalization time rather than color-discrimination time.

Somewhat greater success has been achieved in producing cognitive decrement with tests of simple mathematical skills. Frankenhaeuser (30) found that the speed of multiplication (a 1-digit number multiplied by a 2-digit number) and subtraction (successively subtracting 3 from an initial number) decreases significantly at +3 G_z. In a final series of tests, the subject received auditory presentation of pairs of numbers. The subject added these together and responded by pressing an "odd" or "even" response button. The average speed of response was found to decrease at +4.6 G_z acceleration, although a high degree of variability was evident.

The most thoroughly investigated aspect of higher mental performance under acceleration is short-term memory. Numerous experiments by Chambers and his colleagues, in collaboration with Rutgers University, have shown memory impairment at higher $+G_x$ levels (12, 49, 50). The experimental paradigm involves relatively rapid and continuous responding, and appears well suited to monitoring purposes. The basic task, called running matching memory (RMM), requires that a subject compare the stimulus he sees with one which has occurred a specified number of symbols previously (e.g., 2-back, 3-back, 4-back), and that he press a "same" or "different" button. In the first experiment, plus (+) and minus (-) symbols were displayed on a Nixie tube, and matches were required to be made either 2-back, or 3-back, or 4-back. Stimuli were presented for 4 sec, with a 1-sec intertrial interval. Dynamic tests were all at +5 G_x acceleration for 4.2 min.

The results from this study indicated that +5 G_x acceleration did not significantly affect performance, measured as the mean percent

correct trials (out of 50 trials). Some evidence indicates that the most difficult condition (4-back) was affected by the acceleration; but this effect was manifested as a difference in the shape of its learning curve relative to the other groups, rather than as an actual decrement. The most striking finding was that, even when the subjects in the centrifuge group were tested under static conditions before and after the dynamic runs, their performance was significantly inferior to that of control subjects who did not ride the centrifuge. Because these subjects were inexperienced in riding the centrifuge, their suboptimal performance in the initial static test may have been caused by anxiety or fear--and in the final static test, by residual anxiety or fatigue.

A second experiment incorporated several changes and refinements in technique not only to eliminate some intersubject variability caused by rehearsal strategies, but also to reduce the total testing time, thus making the test practical at higher G-levels. In this study, the subject monitored two displays: On the right, he again saw pluses and minuses; on the left, digits 1 and 2. The two displays went on and off simultaneously, with a 2-sec presentation time and a 0.75-sec intertrial interval. The subject first made a 1-back RMM match for the digits, and then a 2-back match for the arithmetic symbols; hence each trial required two responses. No corrections were possible. Subjects, who were experienced centrifuge riders in this study, were tested at +3 to +9 G_x for 2.3 min. Static tests were interspersed with dynamic runs, to control more effectively for practice effects.

The results showed an overall decline in performance during the dynamic runs at +5, +7 and +9 G_x, but not at +3 G_x. A more detailed analysis revealed that the greatest decrements occurred during the second half of a particular run. Performance decrements were quite similar for the +5 and +7 G_x runs--but, for the +9 G_x runs, errors increased with greater severity and uniformity across subjects. The finding that relatively more G-produced decrement occurred late in a series is noteworthy; for it contrasts with the statement (made earlier in this report section) that practice often serves to counteract the initial G-induced deterioration in performance. Perhaps this discrepancy may be attributed to the previous centrifuge experience of the test subjects in this study. The authors feel that the progressive decrement is not due to cumulative fatigue; for one subject, tested continuously for 4 hours, did not show this decline.

A memory test (of the type just discussed) has considerable appeal as a performance monitoring device during sustained acceleration. Such a test requires only a simple response from the subject; the level of difficulty can be manipulated easily; no excessive practice is necessary before performance stabilizes; a cognitive ability, pertinent to tasks performed by a pilot or astronaut, is measured; and a series of discrete responses are provided, each requiring a short amount of time, so that relatively continuous performance readout should be possible. This type

of test, used successfully in centrifuge experiments, results in a reliable performance decrement at the higher G-levels while being relatively unaffected at the lower levels.

In sum, experiments on the cognitive effects of sustained high-G have been quite sparse to date. The study of higher level cerebral functioning is expected to become increasingly popular in the future, as greater emphasis is placed upon the analysis of specific components responsible for observed psychomotor performance decrements. Such a trend stems logically from many studies, in the early 1960's, to determine the limits under which man could perform "adequately" in space flight. Studies in a more analytical vein are desirable from an applied standpoint, and may also provide the scientific information necessary for fuller understanding of human responses to accelerative stress.

Review and Conclusions--As disclosed by the literature, numerous tasks have been used successfully to demonstrate a performance decline during sustained acceleration. Significant decrements have been observed in various visual functions, in complex motor performance, and in higher mental functioning (an area which has, however, received little emphasis to date).

In the design of a task for centrifuge experimentation, the closest possible consideration must be given to such issues as: the ultimate uses of the test; the types of variables to be studied; the population to which the results will be applicable, and the applied vs. theoretical considerations. Among the general factors to be weighed are the following--(a) to (g):

(a) Level of Practice

In general, a highly practiced subject will be less variable than one with little experience in the specific task.

(b) Centrifuge Experience

Because subjects familiar with a high-G environment know what to expect, they exhibit fewer effects attributable to distraction. On the other hand, for subjects already experienced, performance improvement throughout a centrifuge run should be less likely to occur. Since experienced subjects already know some of the techniques of voluntary physiologic compensation (e.g., the tightening of abdominal muscles), they are also more likely to tolerate the higher G-levels. Nevertheless, even the experienced subjects often exhibit considerable anxiety; and this can manifest itself as a performance decrement before the onset of acceleration.

(c) Motivation

Such groups as jet fighter pilots and astronauts have proven to be highly motivated. Therefore, a test validation based on

subjects who are not pilots may show a performance decrement that is nonexistent for the highly motivated fighter pilot.

(d) Overall Task Difficulty

When the difficulty of a task is increased the likelihood is increased that a performance decrement will appear earlier and at a lower G-level than formerly.

(e) Effect of Components in a Complex Task

If a subject is required to divide his attention among various aspects of a task, then proficiency will be more difficult for him during acceleration stress. His performance on certain aspects of the task may therefore decline markedly, while his proficiency is maintained (or possibly even improved) on other components. Significantly, in a complex test, those parts that one subject chooses to ignore may not be the same for all subjects. To avoid this problem the experimenter should establish differential weightings on the components so that, if a narrowing of attention does occur, the same component will be affected first for all subjects.

(f) Speed-accuracy Tradeoffs

When acceleration stress causes a subject to alter his priorities even in a simple task, the experimenter monitoring an actual run may fail to realize that a performance decline is in progress--or, may incorrectly believe that one is occurring. In an RT task where speed is affected by interest (and where errors can and do occur) a subject may, for example, sacrifice accuracy in order to maintain his speed during a dynamic run. If time to respond were the only variable being monitored, a real proficiency decrement would go unnoticed. In fact, even if provision were made for errors in monitoring, a monitor probably could not determine whether a performance deterioration was truly occurring, if speed began decreasing at the same time accuracy was improving. Again, the best way to avoid this problem is to weight these two factors differentially; for example, by heavily "penalizing" the subject in some fashion for increasing his error rate.

(g) High Fidelity vs. Low Fidelity Simulations

When performance under simulated environmental stress (such as centrifugation) is being investigated, operational relevance must be given careful consideration.

Is it better to use a complex simulated operational task, or a simpler, more abstract, laboratory-type task? The question cannot

be answered concisely; for numerous factors must be considered which pertain to the goals of the respective line of research. McFarland and Teichner (46), who have presented a thoughtful discussion of this problem, maintain that the important issue is: Can performance be maintained within system requirements?

The primary advantage of high fidelity simulation is, of course, its relevance to the real operational situation. The disadvantages may include high cost and maintenance requirements, limited numbers of test subjects, and the difficulty in choosing an appropriate measure of performance decrement. Low fidelity tasks avoid these drawbacks and, in principle, can pinpoint the aspect(s) of psychomotor performance most susceptible to degradation.

In terms of future system performance, is the operator becoming an unacceptable risk? Through this question, the authors (46) argue persuasively against operational simulation. They point out that, in determining the limits of environmental stress to which an operator should be exposed, the total man-machine system performance may remain relatively stable--even while the operator's abilities are being seriously degraded. The limiting environmental stress should be the point at which serious impairment befalls the behavioral mechanisms on which the system performance ultimately depends. Otherwise, by the time that this impairment becomes obvious, the operator may be incapable of recovering. Because of this hazard, the use of relatively abstract laboratory-type tests is strongly advised.

Finally, to supplement all of these factors, a list should be made of additional features to be incorporated in a versatile psychomotor performance test. Many of the following remarks on this subject are excerpted from a paper by Galambos (34) concerning the problem of devising an "all purpose" standardized test for establishing objective endpoints for a given subject's participation in an experiment. Galambos maintained that the onset of nervous system damage may often be the first factor to limit such subject participation, and that the best way to discover this degradation is to test behavior. In order to achieve a test having maximum sensitivity, careful consideration should be given to the six following recommendations (34):

1. Use a few simple and reliable tests rather than attempting comprehensive measurements with a large battery of tests.

2. Automatic or semiautomatic tests are the easier types to administer, and are therefore preferable.

3. Good control studies should be given high priority, so that performance baselines can be firmly established.

4. Attempt to measure the total function of the organism, because it is desirable to "test the eye, the brain, and the hand simultaneously" (34).

5. Because increasing irregularity (or unevenness) of performance is a common result of G-stress, a test sensitive to these lapses is desirable. The best approach is to use a work-paced task, in which the key factors (such as stimulus duration, maximum permissible time to respond, and time between successive problems) are under control of the experimenter. As a result, lapses become more easily discernible.

6. Various conditions involving CNS impairment result in a reduced capacity for storage and retrieval of information. A task that involves memory load will probably increase sensitivity to accelerative stress.

Correlation of G-induced Physiologic/Psychologic Changes

A requirement in the development of the new performance task was that it would afford a determination of behavioral changes, occurring from moment to moment, for subsequent correlation with changes in physiologic parameters which were monitored at the same time. Such comparisons would be expected to contribute to a better understanding of the G-induced decrements in performance. Previous attempts to establish such correlations have therefore been abstracted from the literature surveyed, and are summarized in this report section.

Experimental Results--Relatively few studies have ever been specifically designed to examine the nature and degree of correlation between physiologic and behavioral changes occurring during acceleration. Furthermore, due to the difficulties of standardizing acceleration parameters from different studies, researchers have thus far had little success in combining the physiologic data from one experiment with the performance data from another.

Human visual capability is the one area in acceleration research in which the relationship between a behavioral change and the underlying physiologic mechanisms producing that change is reasonably well understood. Success in this area is probably due to the relative simplicity of the visual response--in contrast to tracking or piloting tasks, for example, which have large cognitive, motor, and motivational components in addition to sensory components. Dimming or loss of vision (blackout) has long been an accepted endpoint for $+G_z$ acceleration runs; as it is a convenient indication of the onset of severe physiologic insult which, if allowed to continue, would quickly lead to unconsciousness.

The loss of peripheral and central vision during $+G_z$ acceleration is related to changes in the hydrostatic pressure between the head and the heart (51). As the acceleration increases in magnitude, this pressure becomes greater until the pumping pressure of the heart is unable to force an adequate supply of blood to the head. Vision is rapidly affected as the blood supply to the brain and visual apparatus is diminished. Due to the fact that intraocular pressure is some 20 mm Hg higher than intracerebral pressure, the blood supply to the retina is diminished before failure of cerebral circulation (32). Livingston (45) has noted

that the oxygen demands of the retina are more critical than those of most other bodily tissues; for even a small decrease in blood supply would be expected to have a marked effect on visual sensitivity. The fact that early visual loss is due to a decrease in retinal rather than cerebral circulation has been demonstrated by Lambert (41), who showed that the use of suction goggles during acceleration will forestall visual blackout. This result has been confirmed by Keighley et al. (39), who also found that acceleration-induced decreases in CFF threshold (the repetition rate at which a flashing light is seen as steady) are of cerebral rather than retinal origin.

Duane (28) conducted the first acceleration study in which careful observations of the retina were made while subjective visual changes were taking place. In this study, subjects reported visual changes that occurred at +4.5 G_z, while a trained observer noted changes in the appearance of the vasculature of the fundus. After approximately 5 sec at peak acceleration, the subject reported peripheral light loss and dimming of the visual field. At the same time, a pulsating of the retinal arteries was observed. A few seconds later, when complete blackout had occurred, the arteriolar tree was emptied of blood and in a collapsed state. These findings have since been verified and extended by means of photographic techniques developed by Leverett et al. (42).

Aside from vision, however, the physiologic correlates of performance changes during G-stress are little understood. For example, the galvanic skin response (GSR), which involves a measurement of changes in the electrical resistance of the skin due to sweating, reflects the arousal level or emotional state of the subject as determined by the activity level of the sympathetic nervous system (43). In addition to the GSR, which is usually defined as a relatively rapid change in resistance level (generally in response to a specific stimulus, such as a light, buzzer, or electric shock), more gradual changes in the baseline resistance level of the skin are often noted in various situations. Such changes in the basal resistance have been observed by Cohen et al. (20) in a series of 10- to 30-sec centrifuge rides at +3 G_z. These changes, which diminished when the subject wore an anti-G suit, were interpreted as reflecting alterations in cardiovascular functioning induced by acceleration. No performance tasks were employed in this early work.

In a later study from the same laboratory, Silverman et al. (54) exposed 6 subjects to a series of 30-sec +3 G_z accelerations, and investigated psychomotor performance changes as well as changes in the GSR. The performance task involved the compensatory tracking of two cross hairs continuously moving away from the center of a dial. The subject attempted to maintain the cross hairs in the center by manipulating a control stick; the performance measure was percent time on target. Skin resistance was monitored from the sole of the foot; and GSR amplitudes were measured both for "spontaneous" GSR activity, and also for "induced" GSR's (initiated by a painless electric shock).

Subjects performed the tracking task less accurately during centrifugation than during a control run, but this decrement was less severe when anti-G protection was furnished. Differences between the protected and unprotected conditions were also observed for the GSR. During acceleration, when no G-protection was provided, the decrease in the average amplitude of an induced GSR was even greater--and the increase of the spontaneous (nonspecific) GSR activity was likewise greater. Apparently, subjects--especially when unprotected during acceleration--are in a state of hyperarousal; for maximum induced GSR amplitude is thought to occur when the subject is moderately aroused, and is functioning close to peak efficiency (19).

In brief, a change in performance during acceleration may be correlated with changes in the arousal state of the subject, as measured by the GSR. Two points must be kept in mind, however, when evaluating the results. First, it was by no means clear that the performance decrement was the result of the observed change in arousal level. Second, the physiologic-behavioral correlation was of a general nature, since the scores on both variables represented the overall averages of numerous 30-sec runs. Because neither measure was sufficiently sensitive to determine moment-to-moment changes, the precise relationship between a physiologic response and a performance decrement during a run could not be assessed. Unless greater sensitivity is attained, utilizing the GSR to evaluate a physiologic-behavioral relationship during acceleration will be difficult at best.

A promising technique for assessing the extent of the physiologic-behavioral correlation, as discussed by Freeman (33), involves monitoring of the average evoked auditory response (AEAR) to repetitive acoustic stimuli. Surface electrodes were placed in the temporal and occipital regions of the skull, and a series of 0.5 msec clicks--at a repetition frequency of 7.9/sec and an intensity of approximately 50 dB--were presented binaurally via earphones. Averages for series of 1000 successive responses were obtained, and the principal components of the AEAR's were identified. Significant differences in certain of these components were obtained during 6-min acceleration runs at $+2.5\ G_z$, as compared with a static control condition. A number of these changes were qualitatively different from those observed during hyperventilation and hypoxia. The results suggest that the AEAR represents a potentially useful technique for monitoring CNS activity during flight, and that it is more sensitive than the EEG (electroencephalogram) to stress-induced changes in CNS activity. The EEG measure has generally been found to be too nonspecific and difficult to interpret to be a useful monitoring technique (18).

The foregoing study (33) indicates that the AEAR is indeed sensitive to relatively low-level accelerative stress. Still to be determined, however, is whether higher levels of G-stress will produce further changes in the shape of the response waveform. In addition, since no experiments have specifically compared changes in the AEAR with changes in a pilot's

ability to perform a particular task, the implied usefulness of the procedure as an adjunct to psychomotor performance testing has yet to be established.

A study by Little et al. (44) dealt with the necessity of measuring simultaneously the behavioral and physiologic changes during acceleration. In this experiment, the G-levels employed were higher (+5, +7, and +9 G_X at peak acceleration for 90 sec) than those in the studies already discussed. One advantage of using higher G-levels is that performance and physiologic changes will probably be more extensive, and a meaningful correlation should therefore be more easily discernible. Moreover, the effects of higher G-levels have increased significance; for performance decrements can be expected to be more severe, and can thus be a greater threat to the success of an actual mission. In measuring performance in this study (44), a discontinuous 2-dimensional tracking device was used. The subject manipulated a control stick in response to lights illuminated in both a horizontal and a vertical array. Performance efficiency was scored as the number of correct responses achieved in each 15-sec period. The physiologic measures reported were heart rate and systolic blood pressure, measured continuously during acceleration and for 60 sec pre- and postacceleration.

The results for the performance task (44) indicated that the decrement occurring during acceleration was significant (as compared with preacceleration scores). Furthermore, the extent of this decrement was positively correlated with the respective acceleration level; unfortunately, however, the difference in performance between the three G-levels was <u>not</u> statistically significant. Presumably, a more sensitive psychomotor task could have distinguished reliably between the G-levels employed. As for physiologic measures, G-stress caused significant increases in heart rate. This tachycardia was significantly related to the G-level, with +9 G_X producing the highest rate. Systolic blood pressure showed an increase during acceleration; but this means of measurement was less sensitive than heart rate, as no significant differences appeared between the various acceleration levels.

According to this study (44), a relationship can be expected between tracking performance and heart rate, when both variables are measured simultaneously during a centrifuge run.

The authors do not present correlation coefficients across the time intervals at peak G, but the data indicate that a correlation would have been only moderately high. The sole <u>firm</u> conclusion is that both the tracking errors and the heart rate increase with acceleration. Because the highest rates obtained were well within physiologic limits, however, there is no evidence that the performance decrement resulted from severe physiologic stress.

In a tracking study (of this type) by Sadoff and Dolkas (53), the performance task involved manipulation of a control stick in order to track a target moving in apparently random fashion across the face of an

oscilloscope. The physiologic measures investigated were heart rate and percent carbon dioxide expired. In -10 G_x accelerations, a small increase in heart rate was noted, although the percent CO_2 remained unchanged. The authors suggest that performance decrement was due, in this case, to other factors (such as visual difficulties produced by lacrimation). With a 2-min +10 G_x acceleration, however, which resulted in a greater tracking decrement than that observed for -10 G_x, heart rate did not change--but the percent expired CO_2 decreased significantly. This reduction reflected the serious respiratory difficulty commonly experienced by subjects at high +G_x acceleration. The authors speculate that the severe performance decline was due largely to the hypoxia that develops as a result of inadequate alveolar ventilation.

Clearly, this study (53) does not represent a major advance in our understanding of the relationship between physiologic and psychologic variables in acceleration. The physiologic measures seem to have been added as an afterthought; no moment-to-moment comparisons are provided between performance and physiologic changes; and the conclusions presented are speculative in nature.

The studies reviewed in this report section indicate that only a few attempts have been made to measure, simultaneously, G-induced changes in both the behavioral and the physiologic variables. The results have generally been disappointing. Indeed, considerable doubt has been expressed by some researchers that the combined physiologic-psychologic approach has a significant probability of success in the near future. The main reason for this doubt is the complexity, in all psychomotor tasks, which makes it difficult (if not impossible) to establish connection between behavioral integrity and the integrity of physiologic system. Howard has stated that "alterations in performance cannot, in general, be predicted from the physiological response to acceleration, because the ability to carry out a task always depends on the functioning of more than one system" (ref. 37; p. 652). Other authors, such as Chambers (14), have stressed that previous research has shown the difficulty of predicting the acceleration thresholds for a performance drop on the basis of those for physiologic changes. The commonly employed physiologic indices have not been reliable or sensitive correlates to the subtle changes in human psychomotor efficiency--especially in comparatively complex tasks which approximate operational conditions.

Another reason for this difficulty, of formulating general principles for the prediction of behavioral change based on physiologic change, is that both physiology and behavior are affected by stress. As pointed out by Hartman (36) changes in a specific physiologic parameter may be evident as the G-level is gradually increased; but measurable behavioral changes may not occur until a relatively hign G-level has been reached--at which time the performance decrement may be sudden and dramatic.

When a better understanding is achieved concerning the way in which psychomotor proficiency is determined by the complex interaction of numerous variables, then the selection of the appropriate physiologic prediction variables may become possible.

Review and Conclusions--In brief, little progress has thus far been made in proving a firm correlation between the G-induced changes in complex psychomotor performance, and those in various indices of the physiologic status of the subject. Only a few studies have dealt, even indirectly, with this question; and they found, at best, a vague relationship between the variables studied. In the opinion of some researchers, correlations adequate for performance prediction are not obtainable. Let us hope that this opinion can be disproven; for it would be a valuable asset to be able to strengthen our understanding of G-induced psychomotor decrement by relating it to one or more physiologic mechanisms (as has been done in the study of visual blackout).

The greatest hope for progress in this area seems to lie in the study of acceleration-induced hypoxia, produced either by cerebral ischemia or by decreased blood oxygen saturation. Consideration information is now available on the effects of $+G_z$ and $\pm G_x$ acceleration on changes in blood distribution and arterial oxygen saturation (32). In addition, the literature on hypoxia (largely derived from altitude-chamber research) includes much information describing the effects of oxygen deprivation on behavioral skills (e.g., 47, 59, 60). At present, a concerted attempt is needed to combine this information and to design experiments for determining, on the basis of circulatory and blood oxygen changes produced by various acceleration environments, the predictable amount of G-induced performance decrement. By comparing the results of centrifuge experiments with those of noncentrifuge studies in which equivalent levels of cerebral deoxygenation are produced, it may be possible to determine the extent to which performance decrement is produced by acceleration hypoxia, rather than by other acceleration-related variables (e.g., mechanical limb loading, vibration, muscular fatigue, and fear). Such an analytic approach appears to offer increased understanding of the physiologic-psychologic relationship during acceleration, and hence merits careful consideration.

TASK REQUIREMENTS

The following four requirements are those formally stated (in the "Statement of Work") in the USAFSAM contract for the human psychomotor performance task which was to be developed and evaluated by Technology Incorporated:

"1. The task should provide a means of assessing the extent of behavioral decrement of a subject experiencing sustained periods of severe

gravitational stress. It should be capable of presenting a "real-time" readout of this decrement--that is, any performance loss should be immediately apparent during the course of the centrifuge run. This stipulation, of course, rules out a great many tasks that would require extensive statistical significance testing, or those in which an entire test must be completed before the data can be averaged and compared with a previous test.

"2. A hard copy record of the results must be provided on a second-by-second time base, for later correlation with observed physiological changes. This requirement eliminates certain kinds of responses, such as verbal responses, and in conjunction with (1) above, rules out any test that requires more than a very few seconds between responses.

"3. The acceleration period during which data can be collected varies from approximately 30 sec to 1 min. Any test requiring greater periods of time in order to provide sufficient quantities of data to determine proficiency level would be eliminated.

"4. The test must be capable of being used in a variety of experimental situations, and must be suitable for use in at least two different acceleration vectors, at levels in excess of $+7\ G_z$, and in excess of $+12\ G_x$. This requirement would obviously eliminate any test that was physically impossible to perform during high acceleration in one of these vectors."

Additional requirements (not formally stated) are clearly necessary. In the following paragraphs these implied requirements (5 to 8) are discussed--as are others which have evolved from our literature survey, and from conversations with the contract monitor, our consultant, and other interested individuals:

5. The task is to be used in a real-time mode, and therefore must be so designed that it can be fully automated. (This requisite eliminates: paper-and-pencil tests; tests that require interactions with the experimenter; and tests that cannot be fully programmed ahead of time.)

6. Because of the high G-stresses to which the subjects will be exposed, and because the test will probably be used in more than one G-vector, the subject's motor activity should be kept at an absolute minimum. The decrement in motor skills is highly dependent upon such factors as: the acceleration vector employed; the nature of the control device operated by the subject; and the strength of the subject. Consequently, tests having a large motor component are of limited value as general research tools, especially when the primary interest is in possible decrements in CNS functioning. In the area of higher mental processes, or cognitive functions, great need exists for research to determine the effects of severe G-stress. Also in this area, the potential is excellent for a properly designed test to show greater functional decrement than that commonly observed in most tracking tasks. For the purposes of the contract, tests requiring minimum movement (such as pressing a few buttons, or making gross movements of a lever) are preferable to tracking tasks that demand precise and coordinated motions.

7. Much of the centrifuge research in which this task will be utilized is designed to study the physiologic and behavioral responses of the jet fighter pilot under severe G-stress. Hence, the task should, at least, require a relatively complex series of cognitive operations that place demands on the information-processing capabilities of the subject. In other words, overly simplistic tasks (e.g., simple dial reading) should be avoided. This is not a plea for high fidelity simulation (already discussed in the "Literature Survey" section) which results in serious problems for the objective measurement of pilot proficiency, but merely an argument in favor of tests that involve some of the basic cognitive skills required of a fighter pilot.

8. To be valuable in different centrifuge experiments, the task should have the capability of involving various information-processing and cognitive operations, and also have the potential for "separating out" as many of these component operations as possible. Through a properly designed task that incorporates numerous performance variables, it is possible to infer the sensitivity of each component operation to G-stress by determining the extent to which each variable interacts with the G-level.

EXPERIMENTAL PROGRAM

As outlined in this report section, the experimental program for USAFSAM included: the general approach; the tasks that have been evaluated; and the reasons for which these tasks were judged suitable or unsuitable. The following material should afford a better understanding of the evaluative procedures, the details which affected the suitability of each task, the tradeoffs necessary between various factors, and the principles discovered (or confirmed) in this program.

Explanation of General Approach

The experimental approach was basically that of trial and error. First, we considered carefully the general requirements which the task must possess to fulfill the needs of the contract. Next, the literature was researched to obtain ideas for tasks which, in principle, seemed most compatible with these requirements. The more promising of these ideas were then utilized in the design of tasks which would be evaluated by studying the performance of trained subjects under normal and hypoxic conditions. The use of hypoxia as a physiologic stress was chosen because it represented a relatively simple and economical means of simulating some of the physiologic effects of sustained gravitational stress (viz, decreased blood oxygen saturation and cerebral ischemia). Subjects were required to breathe from tanks of oxygen-nitrogen mixtures, in which the concentration of oxygen was either 11% or 9%. These levels were chosen as representing moderate levels of hypoxia which should be sufficient to produce some sensory and CNS decrements, without being particularly hazardous to subjects over a short period of time. Each subject wore a nose clip, and breathed the gas through a mouthpiece. Because of the distracting effects of the mouthpiece and of the noise from the demand regulator, the mouthpiece and regulator were employed even when room air was being breathed; and, in this way, uniform conditions were maintained.

A general purpose, prototype, experimental apparatus was constructed (Technology Incorporated) for this study. The apparatus could be used for various tasks which involved the visual presentation of information and required the subject to make one of several discrete responses. The principal components of this apparatus (Fig. 1) were:

<u>A slide projector and screen</u>, for the presentation of up to 100 visual stimuli, at a maximum rate of approximately 1/sec. The projector could be cycled either manually by the experimenter--or automatically, by each response of the subject.

<u>A shutter</u> which, placed in front of the projector, controlled the stimulus-presentation interval. The shutter could be: opened and closed by the experimenter; or opened by the experimenter and closed automatically after a timed interval of 100 msec - 10 sec; or opened by the experimenter and closed whenever the subject responded.

<u>A response box</u>, containing two telegraph keys for the subject to press.

<u>An automatic digital timer</u>, which presented RT to the nearest 0.01 sec--measured as the interval between the opening of the shutter and the pressing of a response key.

<u>A light console</u>, indicating which button was being pressed.

<u>A control box</u>, enabling the experimenter to control the overall functioning of the apparatus.

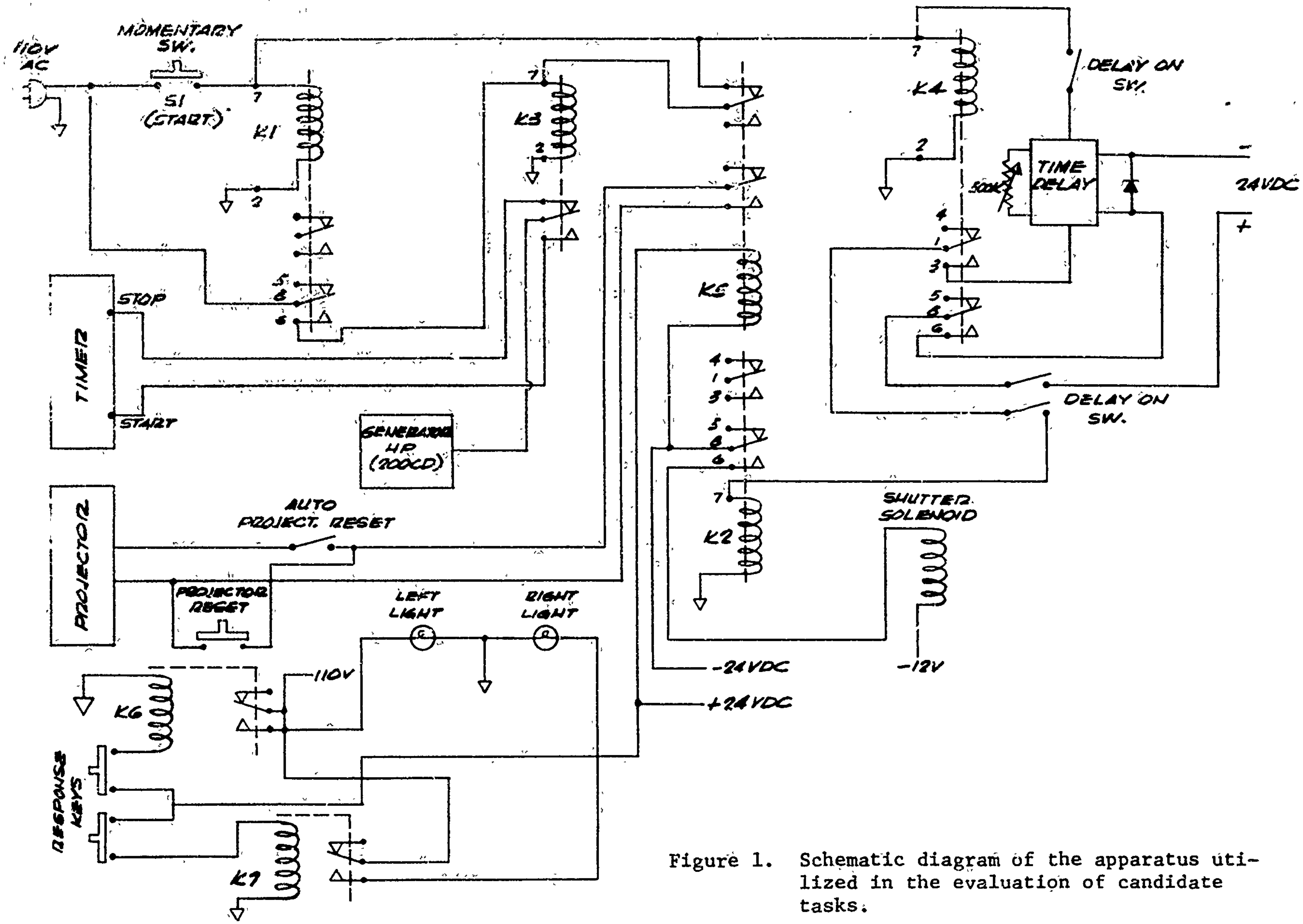

Figure 1. Schematic diagram of the apparatus utilized in the evaluation of candidate tasks.

The experimental program was designed to answer questions concerning the suitability of a particular task for acceleration research. The principal questions were:

1. How much practice is required to attain a reasonably stable level of performance? Can the task be learned as a whole, or does its degree of difficulty require that it be learned in stages? If the task is overly difficult, it may be unsuitable in certain research situations because of the excessive practice required before the experiment.

2. How much variability is observed within and between subjects, after a reasonable amount of practice has been provided? If the variability is too great, performance decrements may be difficult to discern during a centrifuge run.

3. Are there several different ways for the subject to perform the task? (The importance of this question will be made clear in our discussion of certain tasks that have been evaluated.) Basically, if a subject can easily adopt a strategy totally different from that which the task was designed to elicit, then that task is probably unsuitable as a research tool.

4. If the task is designed to measure RT, is the subject able to maintain a low error rate at all times--even after he has received a great deal of practice, and while he is experiencing hypoxia? If subjects can (and do) readily alter their speed-accuracy tradeoffs, it is extremely difficult for an observer to determine accurately whether a performance decrement is occurring, even when errors are monitored along with RT.

5. Is performance on the task adversely affected by hypoxia, and is this decrement great enough to be readily apparent? If not, there is a good chance that performance will be similarly unaffected by sustained acceleration.

6. What happens to the performance score if a subject momentarily breaks his concentration? Such brief lapses are not uncommon under hypoxia and acceleration. The performance measure should reflect these lapses, but the task should be one that the subject can resume.

7. What is the subject's evaluation of the task? (Is it unpleasant, anxiety-provoking, or excessively difficult?) Such evaluations should be considered seriously; for, if a subject cannot or will not sustain his motivation during a session, then the results become almost meaningless.

Evaluation of Candidate Tasks

In the experimental evaluation program, a study was made of variations of a memory and decision-making task that was considered to have

excellent potential for meeting the research requirements. The basic task, termed "running-matching-memory" (RMM), has been used by Chambers and his colleagues (12, 49, 50) in studies of performance decrement during sustained acceleration in the $+3G_x$ to $+9G_x$ range (as described in the "Literature Survey" section). The basic approach in this task is to present a stimulus to the subject, and require that he compare it with one that had occurred at a fixed interval (e.g., 1-back, 2-back, 3-back) before the viewed stimulus. If the two stimuli are identical, he presses the "same" (S) button; otherwise he presses the "different" (D) button. For example, for a 2-back match with the series: 4 2 2 1 2 3 3 3 1 3 1, his responses (beginning with the third stimulus) would be D D S D D S D S S.

We chose this task for many reasons. First, the basic test had been used successfully to show a performance decrement in subjects at G-levels above $+3\ G_x$. Second, the task was considered to be representative, because it incorporated a component of many possible tasks relevant to the environment of acceleration and high-speed flight. Various tasks performed by a pilot or astronaut involve problems of short-term memory and decision making, such as the requirement to monitor visual displays, to retain several current instrument readings, and to make appropriate responses based on those readings. Third, and finally, as Ross and Chambers (49) have noted, other desirable features of this task are that: it represents a single-task rather than a task-sampling approach; the level of difficulty may be readily altered; it requires the ability to abstract and remember information, rather than to perform complex motor skills; it is of short duration; it does not demand excessive practice before performance stabilizes; and it provides for a series of discrete responses, to permit a relatively continuous performance readout. Other researchers have also recognized the value of this type of test. For example, Fraser (32) believed that the most significant area for further acceleration research was that of higher mental functioning, and stressed that this early work of Chambers should be continued.

Several changes in the basic approach were required before the test would be suitable for this program. The most important change was to substitute RT for errors as the dependent variable of interest. In the test's original form, scores were not sensitive or reliable enough to permit its use as a continuous monitoring device; performance could not be evaluated until a session was completed and the necessary statistical tests were made. Therefore we decided to reduce task difficulty to the point at which relatively few errors would be made, and to require that the subject respond as rapidly as possible while maintaining high accuracy. If error probability can be held relatively constant, then changes in the cumulative RT function will provide a ready means of assessing performance decrement during G-stress.

Review of RMM Tasks

In this report section, our various RMM tasks are described, and the experimental results are discussed qualitatively.

The 2-back Discrete Task—The first task to be evaluated was a 2-back RMM task in which stimuli were presented discretely, with the subject's RT score recorded after each response. The terms "discrete" and "continuous" are used here simply to refer to the amount of time between the subject's last response and the presentation of the next stimulus. In a discrete task, the subject's response stops a timer, and the experimenter records the RT before initiating the next stimulus presentation; the interstimulus interval is approximately 3 to 4 sec. In a continuous task, the subject's response initiates the next stimulus presentation, and the only delay between stimuli is that caused by the cycling of the slide projector (approximately 1 sec). In such a task, it is impossible to record manually the RT after each response; instead, the elapsed time for that entire session is recorded, and can be used to calculate the average RT per response. With more elaborate equipment it will, of course, be possible to provide for a truly continuous series (interval of 0 sec), and to permit the automatic recording of RT after each response.

In this experiment the subject was told that, on each stimulus presentation, he would be shown one of four geometric symbols (a circle, triangle, diamond, or cross). His task was to compare the symbol with the one presented as the next-to-last stimulus, and to press either the "S" or "D" button, as appropriate. The subject was seated facing a screen, with his forefinger and middle finger resting lightly on the telegraph keys. As in all subsequent studies, he was instructed to respond as rapidly as possible while maintaining a high degree of accuracy. The intent was not to assure errorless performance (which usually can be accomplished only at a great sacrifice of speed) but rather to strive for an error rate of approximately 5% or less.

Each trial consisted of 52 stimuli, thus requiring 50 responses. Four different trials were prepared; each was constructed to contain equal numbers of all stimuli, and to require equal numbers of same and different responses. The following discussion summarizes what we were able to learn from the data and from the comments and introspections of the subjects. In this study as well as in most subsequent ones, the experimenters participated as subjects; for this participation can often provide more insight into the nature and usefulness of a task than would a great deal of data obtained from other subjects.

For this task, numerous trials were necessary before a subject was sufficiently practiced to have fairly stable RT scores. Shown in Figure 2 are the data from two subjects who underwent 20 trials within several days. A considerable practice effect is observed in the early trials, and approximately 10 trials seem necessary to assure that performance has leveled off. Whether or not subjects should be well-practiced on

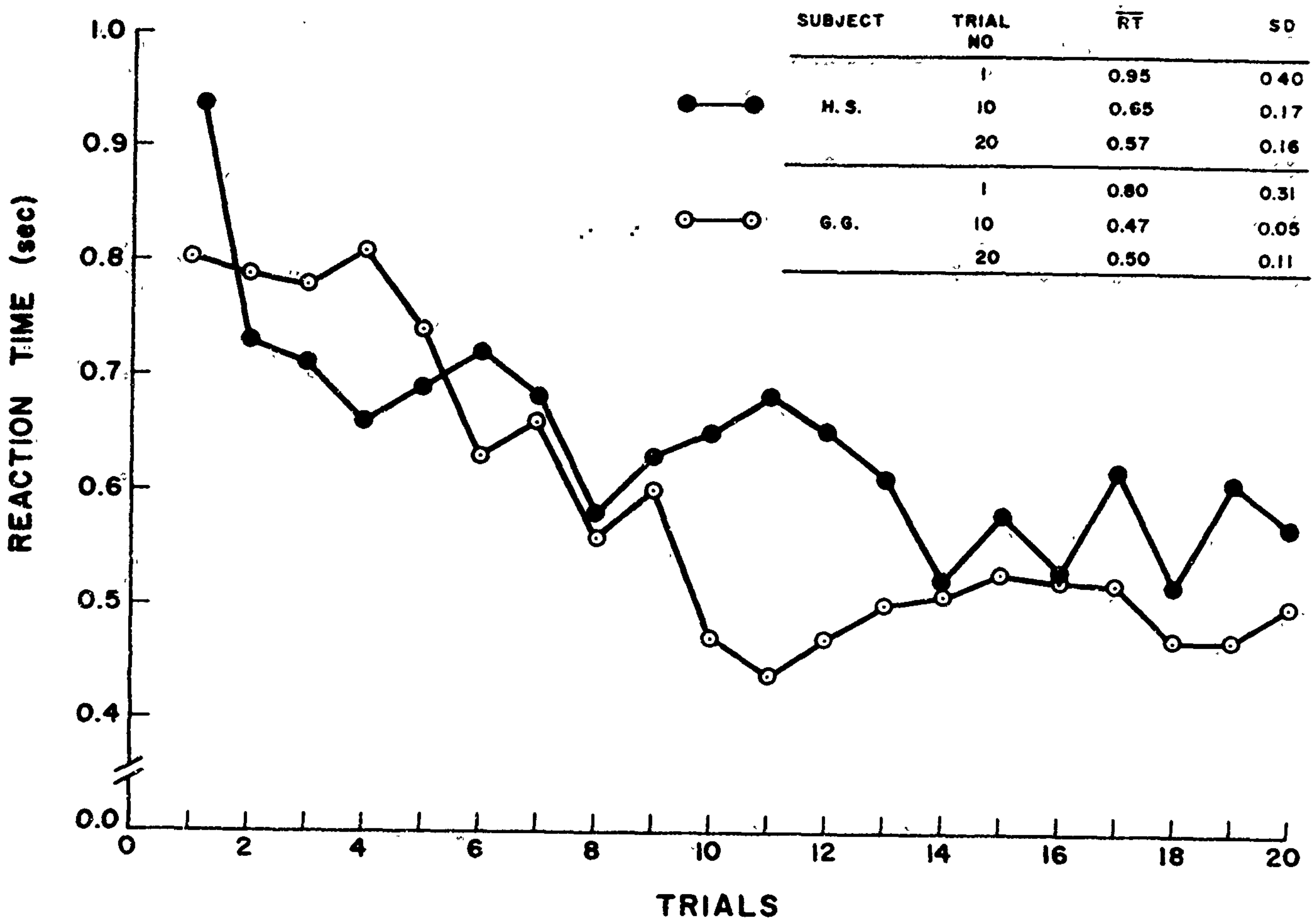

Figure 2. The 2-back discrete RMM learning curves for two subjects. Each trial required 50 responses. Key (inset) shows means and standard deviations for selected trials.

any task used on the centrifuge is a complicated question. Briefly, because a greater amount of practice results in a decreased variability in RT, a smaller change in the performance level will become noticeable or statistically significant. On the other hand, acceleration (or hypoxia) will be less likely to affect performance in a task that is well learned and stable, and that no longer requires a great deal of processing capacity. Thus, if the learning curve is still quite steep, an acceleration-induced performance loss may be partially or totally offset by an improvement in performance due to practice. In the task under consideration, a practice period of 10 trials would seem to be more than adequate. Practical experience indicates that this is a reasonable period for most subjects.

An overall tendency in this task was for the 9% O_2 condition to produce a performance decrement (either increased RT or increased error rate); but, for some subjects, hypoxia seemed to lose its effectiveness after numerous sessions. It was as if these subjects had learned to overcome the effects of hypoxia by "trying harder" in some fashion. This phenomenon might not obscure a larger performance decrement produced by hypoxia, but nevertheless illustrates a potentially serious problem in research of this nature--namely, the importance of motivational level. Research has shown that, even in the case of simple tasks of very short duration, subjects rarely perform at their optimal level under normal conditions. With the proper incentives they can usually be induced to increase their speed with no corresponding decrease in accuracy. Possibly the stress of hypoxia (as well as acceleration) may provide the subject with an added incentive to perform, thereby overcoming the otherwise detrimental effects of the stress. This problem is frequently encountered in stress research, and is best overcome by assuring that all reasonable incentives are provided under baseline and stress conditions alike. Some of the most effective incentives included: competition between individuals; feedback as to one's own level of proficiency; and monetary offerings for improved performance.

One desirable feature of the RMM paradigm is that it involves, for example, memory processes (i.e., encoding, short-term storage, and retrieval) which have been shown to be affected by acceleration and hypoxia. A serious objection to this task, however, is that the present version is primarily a choice RT task that is relatively insensitive to possible memory losses. Of course, the subject's error score can provide an indication of memory loss, because error will occur with a probability of 0.5 whenever the subject cannot remember the identity of the 2-back target. This aspect of the matter is, however, complicated by frequent occurrence of another distinctly different type of error--speed-induced--in which the subject knows the correct answer but, in haste, presses the wrong button. In practice, these errors are usually indistinguishable except to the subject. Thus, while the error scores are at least partially sensitive to memory loss, the RT measure (in which we are primarily interested) is not. The reason for this problem is that the interstimulus interval is long enough for most of the

essential memory operations to be performed between stimuli. If this interval were shortened, the chance would be much greater that a decrement in some memory operation (e.g., encoding of the last time, or reorganization of items in memory) would be reflected in increased RT.

The 1-back Discrete Task--The second task was identical to the first, except that the subject was requested to match the symbol on the screen with the preceding symbol. The relative simplicity of this task was expected to reduce training time for the subject, and thus overcome one of the objections to the 2-back discrete test. The results showed that training time was reduced, along with the intertrial variability, but that hypoxia did not appear to affect RT in any reliable and consistent fashion. This task does not appear to be sufficiently demanding to be affected by moderate hypoxia. With the exception of the ease with which it may be learned, the 1-back discrete task retains all of the faults discussed for the previous test.

The 1-back Continuous Task--This task was identical to the one described in the preceding paragraph, except that the mode of operation was continuous. One theory was that, by decreasing the interstimulus interval, the continuous task might be sufficiently demanding to reflect a decrement in some memory function. It was quickly learned that the task was still too simple, and that no increase in RT was apparent in comparison with the 1-back discrete mode. The memory operations required in this continuous task were so rudimentary that the 1-sec intertrial interval was sufficient for their completion. A zero-sec interstimulus interval would certainly have increased RT, but the task would have remained too simple to be of use.

The 2-back Continuous Task--The 2-back continuous task was chosen to meet the objections of over-simplicity and to place substantial demands on memory operations (as already stated in this report). Of the interesting results obtained, the first was that a totally different type of strategy could be employed successfully in this task. Some of the subjects found that they no longer had to verbalize subvocally the pair of symbols to be remembered for each response.

The exact nature of the strategy is not clear; but, apparently, a visual storage of the symbols is involved--made possible because of the short time-interval between symbols. At any rate, the need no longer existed to name each symbol as it appeared, and to rehearse the names between stimuli, as in the discrete experiment. Unfortunately, now that at least two qualitatively different strategies were available to the subject, making comparisons between subjects (who may be using different strategies) became difficult, if not impossible. Even the same subject might use different strategies on different trials. Such uncertainty was undesirable, for efforts to understand the reason for any G-induced decrement were compounded. Furthermore, with an imagery strategy, hypoxia might not produce the hypothesized RT increase due to memory loss.

In fact (possibly for the foregoing reason), hypoxia produced no consistent performance decrement in our subjects. It seemed necessary to alter the task further, in order to force all subjects into the same strategy--namely, to rehearse each triplet subvocally before responding to the next stimulus. The best way to accomplish this purpose seemed to be: (a) to increase the demands on memory by changing from a 2-back to a 3-back task; and (b) to switch from geometric symbols to numerical stimuli. Thus the length of the match should necessitate the use of a verbalization strategy, and the numbers should simplify verbalizing.

These changes were incorporated in the next type of test.

The 3-back Continuous Task--As already explained, this task was chosen to force the subject to verbalize and to use one strategy consistently--namely, to rehearse a triplet and update (modify) that triplet after each stimulus. By requiring the subject to adopt this strategy, and by making the task continuous, we expected to be able to measure the time needed to perform sequentially several different cognitive operations, some or all of which seemed likely to be affected by hypoxia. (If a discrete mode were used, the subject might have sufficient time between stimuli to "get set," and RT scores would probably be no longer than for a 2-back or a 1-back match.)

A few experimental sessions revealed that this method failed to force the consistent use of a verbalization strategy. One of our subjects had quickly discovered that it was neither necessary nor desirable to update the triplet after every stimulus; for he could, instead, remember a triplet for three trials and then completely change it. (As a brief example: if a stimulus sequence was: 2 1 4 4 3 4 2 3 2, the subject--instead of remembering 214, then 144, then 443--remembered 214 for the first three responses, and then 434. This strategy, although interesting, will not be discussed in detail here.)

Because this unforeseen strategy proved highly effective, we were forced to consider modifying the task to accomplish our objectives.

The 1-, 2-, 3-back Continuous Task--One way to retain the same general requirements, yet induce the subject to rehearse subvocally and to update the triplet continuously, was to provide uncertainty as to the number of previous items with which a stimulus must be compared. If on each trial the subject does not know whether he will be required to make a 1-, 2-, or 3-back match, his optimal strategy seems to be fairly well specified. For each response he must remember the identity of the last three stimuli, and the order in which they were seen.

According to our new procedure, on each stimulus presentation the subject saw simultaneously: (a) one of four stimulus letters (B, F, K, N); and (b) one of three numbers (1, 2, 3). The number appeared above the letter. The subject was instructed to remember the last three letters presented, in their order of appearance, and to respond according to whether the stimulus letter corresponded to the letter occupying

the position in the triplet specified by the accompanying number. For example, in the following sequence of stimuli:

2	1	3	3	2	2	1	1	3	3	2
F	N	K	B	K	B	F	K	K	B	N

the subject begins by remembering the triplet FNK. Since B does not occur as the third member of that triplet, he responds: "Different" (D). He then updates his triplet, and remembers NKB. Since the next stimulus is 2 - K, and the second member of that triplet is K, his response is: "Same" (S). Subsequent responses are: S, D, S, S, D, D.

Reports from subjects confirmed that this task was successful in forcing them to verbalize and update the triplets continuously. Even after extensive practice, no alternative methods for performing accurately were feasible. Unfortunately, however, the task was hard for subjects to learn to perform accurately; and, even after considerable practice, the RT scores and errors were high. Similar problems were encountered in the discrete mode. In addition, some subjects never did learn to perform adequately, and simply gave up trying after a number of sessions.

Another serious problem pertains to any task requiring retention of item information from three or more previous stimuli. If for any reason a subject forgets the triplet he is trying to remember, it is extremely difficult--even for a well trained subject--to get back on the right track and begin responding again. Hence, if this problem arises during a centrifuge run (which is probable), the subject may cease to respond altogether. The decision was therefore made to require the subject to remember only the preceding <u>pair</u> of stimuli, rather than the preceding triplet.

Selection of the 1-, 2-back RMM Task

The sole difference between this 1-, 2-back task and the 1-, 2-, 3-back continuous task is that only three possible letters occurred (B, K, N) and only two digits (1, 2). Simplifying the task to this extent vastly improved the ease with which it could be learned, improved the motivation of subjects who had formerly experienced great difficulty, and virtually eliminated the problems of resuming the task after an attention lapse.

The length of each trial was decreased to 42 stimuli (40 responses). Four slide reels were prepared, each with a different sequence of letters and digits. These sequences were randomized, with the restrictions that there must be equal numbers of S and D responses, and that each digit and letter must occur with approximately equal frequency.

This task was evaluated under the two following stress conditions: hypoxia and alcohol intoxication.

<u>Hypoxia Trials</u>--In this study, subjects were tested while breathing either normal air or a mixture of 9% oxygen and 91% nitrogen.

Subjects wore a noseclip and performed all tests while breathing through a mouthpiece connected by a flexible hose to the cylinder of gas. During control runs, the demand regulator was switched to allow the subject to breathe room air.

This experiment was run in the "continuous" mode, with each response causing the projector to cycle and present a new stimulus. Thus, individual RT's were not obtained in this study; the data represent the average time required to complete 40 responses (minus the machine cycling time), divided by 40.

All subjects were thoroughly familiar with the task at the beginning of the experiment, having received a minimum of 10 practice trials on previous days. On each day of the experiment, the subject was given one practice or warmup trial. His score was not recorded on this trial During the experimental session, he received: one trial while breathing normal air; next, three trials while breathing the reduced oxygen mixtures; and, finally, one trial while breathing normal air. The three hypoxia trials were begun 5, 10, and 15 min, respectively, after the subject began breathing 9% oxygen. The post-hypoxia trial began 10 min after the subject was switched back to room air (15 min, if he reported still feeling dizzy or drowsy).

In Table 1 are presented the data averaged across the four subjects tested (two subjects were tested on 3 different days; one on 4 different days; and one on 5 different days). An average increase in RT of approximately 7.5% was obtained under hypoxia conditions. The statistical significance of this increase was <u>not</u> calculated; however, the percentage increase is approximately the same as for the data to be presented in the following section (on which statistical tests of significance <u>were</u> performed).

Because these results were considered encouraging, a more elaborate and carefully controlled experiment was conducted in which alcohol was used as the stressing agent.

<u>Alcohol Sessions</u>--In this study, four subjects were tested at various intervals after ingestion of a carefully measured dose of ethyl alcohol. Each subject was tested on 6 different days, during a 2- to 3-week period. Days 1, 3, and 5, were practice sessions; days 2, 4, and 6 were alcohol sessions. On the first two alcohol sessions, subjects received an 8:1 mixture (by volume) of orange juice and Everclear (190 proof), where the dosage of Everclear was calculated to be 1.0 ml ethyl alcohol/kg body weight. ("Everclear" is a registered trademark of the American Distilling Company.) On the third alcohol session, this dosage was increased to 1.5 ml/kg.

Individual RT's were recorded, so that the data for each trial consisted of 40 RT scores. In order to record each score and yet keep the task as nearly continuous as possible (interstimulus intervals of approximately 1 sec), the experimenter read each response (RT and button

pressed) into a tape recorder, and later transcribed the data. To avoid distractions, the subject wore earphones which masked the sound of the experimenter's voice.

Each practice session consisted of six trials; each alcohol session consisted of two baseline (pre-ingestion) trials, and four post-ingestion trials. After the baseline trials, subjects were given 15 min (25 min on the final session) to consume the orange juice-Everclear mixture. Trials were then run 20, 40, 60, and 80 min after cessation of drinking. Immediately before each trial, the subject's blood-alcohol content was measured by means of a "Breathalyzer" (registered trademark of the Stephenson Corporation). All subjects had been instructed to abstain from eating for 4 hours before the experiment.

Summarized in Table 2 are the results of this study, presenting RT and error data for the three practice sessions (A, B, C) as well as the alcohol sessions (I, II, III). Several aspects of these results should be noted. First, the baseline RT performance improved steadily from the first practice session (1.075 sec) through the third alcohol session (0.634 sec). Only a slight improvement would be expected beyond this point, as the decrease in RT (to 0.642) on the final day was only 0.008 sec.

In connection with this practice effect, we noted that the influence of alcohol on performance diminished with increased amounts of practice. On the first day that subjects received alcohol (session I), RT scores increased 0.81 sec in comparison with baseline levels on that day. An analysis of variance showed this increase to be statistically significant ($P < .05$). In session II, where the blood-alcohol content was virtually identical to that in session I, the RT decrement was only 0.025 sec, thus failing to be statistically significant ($P > .05$). Finally, with a 50% increase in the alcohol dosage for session III, a significant decrement of 0.060 sec was observed ($P < .01$). Therefore, extensive practice may render this task less likely to be degraded significantly, at least when alcohol is the stressing agent. Due to the design of this experiment, however, an alternative explanation is possible. Perhaps the subjects learned to compensate for the effects of alcohol, so that the performance decline in session II was less severe--not because the subjects had more practice on the task, but because they had practice performing while intoxicated. Further experimentation would be necessary to resolve this question fully.

As for the error scores, these were fairly stable across sessions. Errors did increase slightly in the alcohol sessions, but this increase averaged only about one error per trial. Although (ideally) no such increase should occur, our efforts to induce subjects to maintain a constant error rate were reasonably successful.

In summary, this experiment has shown that performance on the 1-, 2-back RMM task will indeed be degraded substantially by low-to-moderate

TABLE 1. SUMMARY RESULTS OF THE EFFECT OF HYPOXIA (9% O_2, 91% N_2) ON PERFORMANCE OF THE 1-, 2-BACK RMM TASK

	Condition						
	Normal pre-test	Hypoxia trials 1	2	3	Normal post-test	Average normal	Average hypoxia
Average RT (sec) per response	0.723	0.767	0.780	0.777	0.718	0.721	0.775
Average errors per trial	1.8	2.4	3.2	3.3	1.5	1.7	3.0

TABLE 2. SUMMARY RESULTS OF THE EFFECT OF ALCOHOL ON PERFORMANCE OF THE 1-, 2-BACK RMM TASK

	Sessions					
	Practice A	Alcohol I	Practice B	Alcohol II	Practice C	Alcohol III
Average blood-alcohol content per session		0.072%		0.074%		0.105%
Average RT (sec) per response:						
Baseline	1.075	0.821	0.758	0.689	0.642	0.634
Alcohol		0.902		0.714		0.694
Average errors per trial:						
Baseline	2.4	1.8	3.1	3.3	2.4	2.0
Alcohol		2.3		3.8		3.9

levels of alcohol intoxication. This test, therefore, not only possesses the requisite features of a real-time monitoring device, but also is susceptible to the two kinds of physiologic stress investigated. We thus feel confident that a similar performance decrement will be produced in a high-acceleration environment of sufficient magnitude and duration to diminish substantially the flow of blood to the brain and/or the blood oxygen saturation level of human subjects.

FINAL RECOMMENDATIONS

On the basis of our research results, the 1-, 2-back RMM task receives our recommendation for the performance task which meets the needs of USAFSAM. (We realize, of course, that it is not the only task which could be used successfully to study cognitive decrement produced by sustained acceleration.) We have two main reasons for selecting this task--it shows a substantial decrement under two types of physiologic stress, and it can show a cognitive impairment at high G-levels. The 1-, 2-back RMM task eminently fulfills the requirements of the contract with USAFSAM.

The Psychomotor Task

The basic character of the task (as already described) is that either the digit 1 or 2 is presented along with one of three letters, and the subject is required to make one of two responses as rapidly as possible. He presses the "S" button if the letter presented matches either the first or second member (depending on the digit) of the most recent pair of letters. If there is no match, he presses the "D" button. The best response arrangement is to position the two buttons near the subject's right hand, so that they may be operated by his index and middle finger. Stimuli should be high in contrast, positioned directly in front of the subject, and large enough to be easily readable. The choice of stimulus letters is not critical; in most experiments, the letters selected should be easily discriminable and phonetically dissimilar. Stimuli other than letters (e.g., geometric symbols) may be desirable in certain experiments.

The total length of a trial should not exceed approximately 1 min. This trial length is compatible with the duration of a high-G run, and is short enough to preclude a performance decline due simply to loss of concentration. The number of stimuli (or responses) per trial should be approximately 40 to 60.

The duration between a response and the presentation of the next stimulus should be brief (0 to 0.5 sec). A 0-sec interval is probably best, as it prevents the subject from performing any cognitive operations while the clock is not running.

The minimum practice before an experiment should be two sessions of five trials each. If the subjects must be well practiced before being

tested, seven or eight sessions of five trials each is recommended. The number may vary, depending upon the intelligence level of the respective subject population.

The importance of a low and consistent error rate must be stressed. An error rate of approximately 5% should be the goal. Hence, after a few practice trials, it may be necessary to instruct some subjects to respond either faster or slower. One effective procedure (depending on the subject population) is to reward good performance monetarily, and to establish a payoff matrix which heavily penalizes excessive errors.

For psychologic research of this type, the importance of having a well-motivated subject panel cannot be overemphasized. Best results are always obtained when subjects are eager to perform to their utmost, day after day. To maintain high morale, the experimenter should establish good rapport with each subject, make sure that each is aware of the importance of the research, and explain the experiment in detail. Providing feedback, as to the subject's level of proficiency, is almost always desirable; and it is sometimes helpful to establish friendly competition between subjects, or to provide monetary rewards for a performance improvement. A skillful experimenter can vary his approach according to the respective subject population.

Automated Performance Testing System and Subsystems

In preparing specifications for an Automated Performance Testing System (APTS)--to implement the 1-, 2-back RMM task--considerable thought was given to insuring its usefulness for many future years. As a result, versatility is one of the assets specified in the system. Its applicability ranges from simple RT tasks to complex problem-solving experiments on visual research, character classification, pattern recognition, perceptual comparison, mental arithmetic, and vigilance. The APTS could be used not only in acceleration studies, but also (due to its portability) in studies of the effects of hypoxia, carbon monoxide, alcohol, drugs, and stressful environments.

In brief, the functions of the APTS are:

(a) to present, automatically, a series of visual stimuli to the test subject. The number and nature of these stimuli should be variable, as should the stimulus-sequencing characteristics (stimulus duration, interstimulus interval).

(b) to permit the subject to make one of a number of discrete responses.

(c) to record and display, automatically, information concerning the subject's speed and accuracy of response. The information displayed should also constitute an analog record of the subject's cumulative performance across a trial, so that the experimenter can immediately note any deviations from a baseline record (simultaneously displayed).

Display and Response Subsystem--The display subsystem for the APTS should be designed for installation on the SAM centrifuge and be capable of withstanding ±15 G's on any axis. The display console should consist of a minimum of five individual displays, each capable of presenting at least ten individually addressable characters (numerical, alphabetical, or symbolic). To adapt to the changing test requirements, the characters available from each display should be easy to revise. Each display should present a viewing surface at least 2.5 cm high by 1.5 cm wide. The interface wiring between the display console and the control console (including all display power) should be limited to thirty (preferably fifteen or less) 600-ohm, twisted pair (unshielded) wires which are 60 m long, with a maximum voltage of 120 V rms and a maximum current of 5 A rms. The total weight of the display console must be less than 45 kg. The response unit for the system should consist of four (normally open) push-button switches, providing a closure to ground when depressed. These switches should be mounted on a small chassis that may, in turn, be so mounted on the equipment that the buttons are under the fingers of the subject's right hand.

Control Subsystem--The triple purpose of the control subsystem is: to control a preprogrammed sequence of stimuli through the display subsystem, to evaluate the subject's response, and to supply control signals to the readout subsystem. Changes from one test program to another (each program capable of presenting at least 150 individual sets of stimuli) should require minimum time and effort by the investigator. The control subsystem console should be designed to give the experimenter continuous control of the stimulus presentation interval and the interstimulus interval so that, depending upon the respective test, the following stimulus-sequencing modes are available: (a) The displays are activated until the subject makes a response, at which time the stimuli disappear. A new set of stimuli is then presented either immediately or after a predetermined delay of 0.1 to 9.9 sec. (b) The displays are activated for a predetermined interval (again, 0.1 to 9.9 sec). The stimuli then disappear until the subject responds, at which time new stimuli are presented. If the subject responds before the interval is completed, the stimuli will remain visible until the end of the predetermined interval, and new stimuli will immediately appear. (c) Stimuli are presented for a predetermined interval after which new stimuli are immediately presented. The subject's response has no effect on the appearance or disappearance of the stimuli. (d) Same as the (c) mode, except that a predetermined delay occurs between the stimulus offset and the start of a new trial.

The control subsystem should be capable of: (a) detecting a minimum of four different subject responses; (b) ignoring subsequent responses to the same set of stimuli; and (c) determining if the response is correct or incorrect. The sequence of correct responses is determined by the test program.

Readout Subsystem--The readout subsystem should consist of two major components and their associated control circuitry: (1) a digital

hard-copy printout of the subject's response to each set of stimuli; and (2) an analog hard-copy plot of the subject's cumulative response time.

The digital printout should yield one line of digital information for each set of stimuli presented to the subject. As a minimum, this information should include:

(a) a sequential step identifier, providing nominal identification of each set of stimuli within a trial;

(b) the subject's response time (RT) to that set of stimuli, to a maximum of 9.99 sec with a 0.01 sec resolution and a ± 0.01 sec accuracy: and

(c) a positive indication when the subject has made an incorrect response.

The analog plot should yield a real-time graphic display of the subject's cumulative RT from beginning to end of a trial, and should provide:

(a) a positive indication of each new stimulus presentation;

(b) a positive indication of each incorrect response;

(c) a continuously adjustable time-scale ranging from 2.5 to 0.25 cm/sec;

(d) capability of displaying 60 sec of cumulative RT at the 2.5 cm/sec slew rate;

(e) an accuracy of ±0.6 sec/min for cumulative RT at any response rate, up to 150 responses/min;

(f) a continuously adjustable response scale, ranging from 2 to 8 responses/cm; and

(g) a zero reset capability--allowing the baseline test (unstressed) and the test under stress to be recorded, in different colors, on the same graph.

General Requirements--The APTS should be designed to operate from 110 V rms, 60 Hz commercial power, with all power supplied to the display console through the display-control interface. The display console should be designed to operate from +15°C to +40°C and under ± 15 G acceleration on any axis. The control and readout subsystem should be designed to operate from +15°C to +40°C in a laboratory environment.

The system should be capable of being expanded to accommodate more than 5 display units (to a maximum of 20 units) without major mechanical or electronic redesign of the control unit.

The system should be mechanically designed and interfaced to facilitate not only its removal from the centrifuge but also its installation in other test areas.

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ABBREVIATIONS AND SYMBOLS

A	ampere(s)
AEAR	average evoked auditory response
AMAL	Aviation Medical Acceleration Laboratory
APTS	automated performance testing system
CFF	critical fusion frequency
CNS	central nervous system
CRT	cathode ray tube
D	different
dB	decibel(s)
EEG	electroencephalogram(s)
fL	foot-lambert(s)
GSR	galvanic skin response
$+G_z$	acceleration through longitudinal axis of body, with the inertial resultant in a downward direction ("eyeballs down") positive acceleration
$+G_x$	forward acceleration, with a resultant tissue displacement towards the back ("eyeballs in")
$-G_x$	acceleration producing anterior tissue displacement ("eyeballs out")
$\pm G_x$	transverse acceleration
Hz	Hertz
LOMA	limitation of ocular movements under acceleration
min	minute(s)
mL	millilambert(s)
RMM	running matching memory (test)
rms	root mean square
RT	reaction time
S	same
S.D.	mean difference (standard deviation)
sec	second(s)
USC	University of Southern California
V	volt(s)
WADC	Wright Air Development Center